Plausible Energy Futures:

A Framework for Evaluating Options, Impacts, and National Energy Choices[1]

An MIT Energy Initiative Working Paper

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Executive Summary

The global energy system is undergoing major transformations. The world faces a dual challenge of meeting increasing energy demand while reducing greenhouse gas emissions. This change is characterized by the convergence of power, transportation, industrial, and building sectors, and the surge of multi-sectoral integration. Such transformation of energy systems requires a combination of technology selection and policy choices to ensure providing reliable and clean energy. Understanding the implications of these dynamics is challenging and requires a holistic approach to provide systems-level insights.

In this working paper, we provide an overview of energy transformation analysis and projection tools and discuss the use of quantitative methods to examine possible future energy pathways. This is done to facilitate achieving decarbonization goals by providing thought leaders and policy makers with a robust framework in which energy choices and decarbonization goals can be made based on lifecycle analyses. We synthetize our findings applicable to modeling tools based on discussions with colleagues in other academic institutions and government labs and provide a summary of a wide range of lifecycle assessment (LCA) and energy modeling tools.

Our assessment shows that although there is considerable related research work emerging, there is a lack of readily available or generally accepted quantitative models and tools that consider a broad and robust lifecycle analysis approach for a range of plausible energy futures at regional and national levels. Such a tool is needed to help policy makers, industry, investors, and the financial sector to better understand and make decisions on energy choices and energy transitions, and avoid narrowly-framed and advocacy-driven pathways.

We at MIT have substantial experience in building and maintaining energy system assessment tools:

i) A comprehensive system-level and pathway-level lifecycle assessment model, which is called the Sustainable Energy Systems Analysis Modeling Environment (SESAME). SESAME is a publicly available, open access model with multi-sector representation.

ii) The Integrated Global System Modeling framework (IGSM), which combines an economy-wide, multi-sector, multi-region computable general equilibrium (CGE) model (The MIT Economic Projection and Policy Analysis model, EPPA) with a natural systems component (The MIT Earth System model, MESM). The IGSM is an integrated assessment model (IAM).

To quantify additional environmental impact categories such as air pollutants and water footprint, we develop an expanded SESAME platform. For an economy-wide scenario analysis, we use the

modeling results from our EPPA model. The expanded SESAME version will be a publicly available technology options and scenario analysis tool that can use input information from any economy-wide system (or use the default settings that represent our base-case values). The tool will evaluate options, impacts, and national energy choices for exploring the impacts of relevant technological, operational, temporal, and geospatial characteristics of the evolving energy system. It focuses on lifecycle analysis with high technology resolution (linked with the existing MIT energy-economic models) that provides economic information and quantifies lifecycle GHG emissions, as well as impacts related to criteria pollutants and water. Such analysis highlights how effective policy choices and technology selection can reduce such environmental impacts.

1. Introduction

Providing universal access to clean, affordable, and reliable energy, while considering the diversity of resources at local, regional, and national levels is necessary to meet sustainable development goals (IEA, 2019). As the contemporary global energy system faces the dual challenge of increasing energy supply while simultaneously reducing greenhouse gas (GHG) emissions, the need to fully understand the technology challenges and plausible pathways to meet this challenge has become critical. Energy consumption transformations are encouraged by both policy drivers and technology innovations as nations commit to goals to limit global warming to 1.5°C. This implies reaching net zero CO_2 emissions globally around 2050 with concurrent deep reductions in emissions of non-CO_2 emissions (particularly methane) (IPCC, 2018). Climate change mitigation pathways require technology advances to reduce CO_2 emissions. Mitigation measures will likely also necessitate decarbonizing electricity and transportation, electrifying energy end use, reducing agricultural emissions, and sequestering carbon dioxide with carbon storage on land or in geological reservoirs. Technological innovations can contribute to limiting warming to 1.5°C, for example, by enabling the use of smart grids, energy efficient appliances, energy storage, and hydrogen or advanced biodiesel (IPCC, 2018) (IEA, 2019). Such strategies and technology innovations or a combination of both might be an optimal solution for a specific region to reduce emissions.

Figure 1 shows IEA projections for primary energy demand and related CO_2 emissions in three different scenarios: a) the current policies scenario, in which the world continues along its current path with no additional changes in policy, b) the stated policies scenario (STEPS), which by contrast to the first scenario, incorporates today's policy intentions and goals, c) sustainable development scenario (SDS), which lays out a way to reach the United Nations Sustainable Development Goals (SDGs) most closely related to energy. These goals include achieving universal energy access, reducing the impacts of air pollution, and tackling climate change to meet the Paris Agreement (IEA, 2019). In all three scenarios world economy grows by 3.4% per year.

It is projected that primary energy demand grows by a quarter to 2040 in the stated policies scenario, which explores the implications of announced targets and current energy policies. Average energy demand growth is also projected to be 1% per year, which is well below 2.3% seen in 2018 (IEA, 2019). In such a scenario, all fuels and technologies (led by gas and renewables) contribute to meeting the primary energy demand growth except for coal (Figure 1). Oil demand flattens after 2030 due to improvements in fuel efficiency as well as electrification of mobility.

Regarding final energy consumption (Figure 2), the industry sector accounts for the largest share of growth (35%) in the stated policies scenario, nearly all of which is in the form of natural gas and electricity. In the transportation sector, less than half of the growth demand is met by oil, which is a significant change from previous trends. Electricity and biofuels together account for half the growth in road transport demand, which is noticeably higher than the 30% from oil products (IEA, 2019).

In the sustainable development scenario, energy efficiency policies lead to lower energy demand in 2040 than today. In such a scenario, there is a rising share of low-carbon energy accompanied by reduction in coal use and while there is a reduction in oil and gas use, they still remain as a significant portion of the energy mix in 2040 (Figure 1) (IEA, 2019). In this scenario, flat industrial energy demand to 2040 is mainly due to improved material efficiency (Figure 2). Also, considerably higher fuel efficiency and increased rate of electrifying vehicles lead to reduced energy consumption in transportation sector (Figure 2) (IEA, 2019).

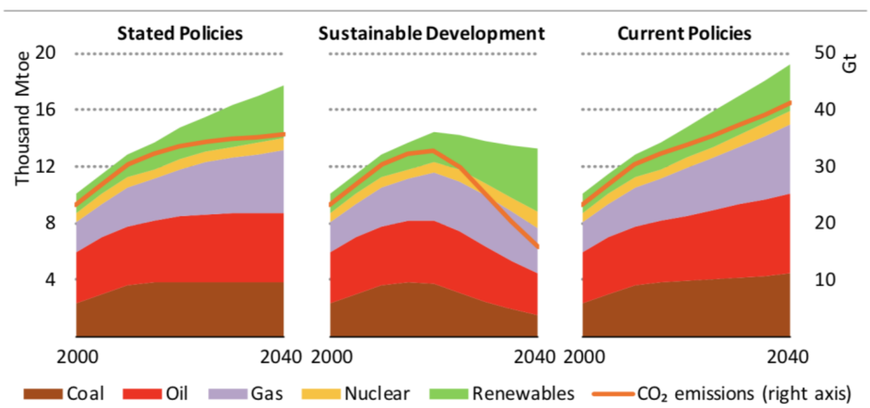

Figure 1 Global primary energy demand by fuel and related CO_2 emissions across stated policies, sustainable development, and current policies scenarios (IEA, 2019).

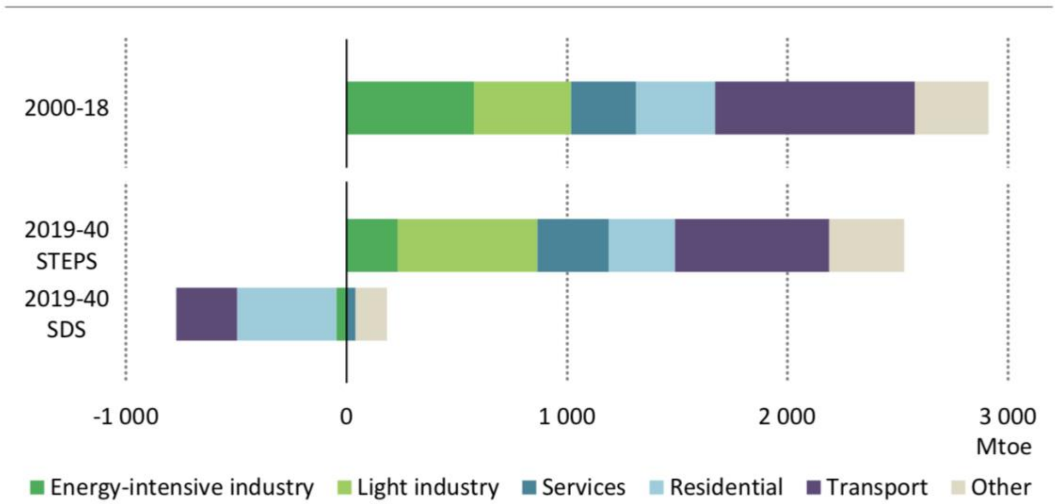

Figure 2 Change by final energy consumption across sectors and scenarios (IEA, 2019).

Significant reductions in energy-related CO_2 emissions are required in the sustainable development scenario, which highlights the need for significantly more ambitious policy actions in favor of efficiency, carbon capture technologies, clean energy technologies, and energy conservation measures. Figure 3 shows the role of different sources in reducing CO_2 emissions in the sustainable development scenario compared to the stated policies scenario, which reflects the actions of today's policy makers regarding energy markets, energy security, and emissions.

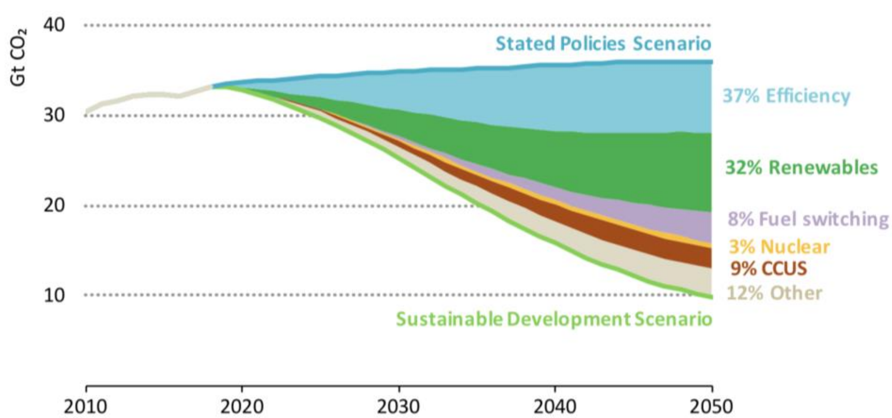

Figure 3 Energy-related CO_2 emissions and reductions by source in the Sustainable Development Scenario compared with the Stated Policies Scenario (IEA, 2019).

According to the IEA (2019), to meet SDGs and global warming limitation goals, energy efficiency improvement is the main recommendation in most regions, because of its cost-effectiveness, but energy efficiency improvement alone cannot meet the emissions reductions required to achieve the SDGs. The other principal option for reducing CO_2 emissions is the deployment of renewables, supported by policies that further strengthens their competitiveness vis-à-vis fossil fuel power (such as carbon prices). The cost of these technologies, particularly solar PV and wind, has fallen significantly in recent years and is expected to decline further. Integration of renewable energy technologies in the industry and buildings (for heating purposes) and transport (advanced biofuels) sectors has been limited, given high costs and lack of sufficiently widespread policy support.

Another technology that can help decarbonize the economy is carbon capture, utilization, and storage (CCUS). The potential for the deployment of CCUS in the power sector differs by region. For example, in countries such as China and India, the carbon capture potential is high assuming that there is political and social willingness for CO_2 sequestration, as coal plants are very young. Such newly built coal plants have an expected lifetime of 50-60 years and therefore, their retirement in an early stage might not be economically viable. A similar potential exists for natural gas plants in the United States, where natural gas prices remain low and a young fleet of natural gas plants retrofitted with CCUS can provide cheap and potentially flexible power generation. In addition to the power sector, the use of CCUS in industrial applications is likely to be widely needed, as emissions from energy-intensive sectors are typically hard-to-abate. Therefore, CCUS is one of the few currently available technologies to achieve deep levels of decarbonization in such sectors (IEA, 2019). Governments would need to take steps to enable a framework to foster the deployment of CCUS as the decarbonization of hard–to-abate sectors become more critical over time.

Current policies and energy technologies shape the trajectory of the energy sector in the years ahead. Low-carbon transformation of the energy system requires a combination of technology and policy options to ensure reliable, affordable, and clean energy. Such options vary across geographies due to specific characteristics of each region in terms of main economic sectors and those that contribute to GHG emissions. The developing economies will continue to pursue greater prosperity, and therefore identifying efficient technologies that provide energy to such regions in an environmentally responsible way is more realistic and likely to succeed. An assessment of plausible country-specific transition pathways can be guided with a set of quantitative methods and assessment tools. Such tools cover multi-sector dynamics of transitions and consider economy-wide and sectoral lifecycle analyses of numerous options, while highlighting trade-offs to provide decision-making insights to government stakeholders.

For example, integrated assessment models (IAMs) can build the foundation for the mitigation pathways, as they combine insights from various disciplines in a single framework, resulting in a dynamic description of the coupled energy-economy-land-climate system that cover the sources of anthropogenic GHG emissions from different sectors. This allows for the exploration of the whole-system transformation, as well as the interactions, synergies, and trade-offs between sectors (IPCC, 2018). Economy-wide, and in particular computable general equilibrium (CGE) models, offer a powerful analytic tool to analyze energy and climate policies and technology options and to tailor them to avoid potentially burdensome consequences for the economy. By design, CGE models provide an economic/financial lifecycle assessment of production-consumption flows. These models are described as general equilibrium because they simultaneously solve for all outcomes in all markets.

Though CGE models are critical to test policy and technological options and scenarios, Lifecycle Assessment (LCA) models are an important component for an in-depth analysis of the performance and environmental consequences of technology choices. LCA models typically focus on representation of the physical supply chain of multiple one-product pathways. They are important tools for the assessment of material balances and environmental impacts incurred during the cycle of production-consumption-disposal. LCA quantifies a product's environmental impacts through input-output accounting of processes from cradle to grave.

This working paper presents an assessment of energy modeling tools and methods as well as MIT's current generation of modeling tools associated with energy choice evaluation:

i) A comprehensive system-level and pathway-level lifecycle assessment model, which is called the Sustainable Energy Systems Analysis Modeling Environment (SESAME). SESAME is built in a modular structure' and it simultaneously covers various sectors and their interconnections, such as the road transportation, power, industrial and residential sectors.

ii) The Integrated Global System Modeling framework (IGSM), which consists of an economy-wide, multi-sector, multi-region, computable general equilibrium (CGE) model (The MIT Economic Projection and Policy Analysis model, EPPA) and the natural systems component (The MIT Earth System model, MESM). The IGSM is an integrated assessment model (IAM).

To quantify environmental impact categories such as air pollution and water footprint., we are expanding the scope of the SESAME platform. For economy-wide scenario analysis, we use the modeling results from our EPPA model to inform our proposed technology assessment platform as an exogenous input. The expanded SESAME version will be a publicly available technology options and scenario analysis tool that can use inputs from various projections including economy-wide modeling tools such as EPPA (or use the default settings that represent our base values). The tool will evaluate options, impacts, and national energy choices for exploring the impacts of relevant technological, operational, temporal, and geospatial characteristics of the evolving energy system. It focuses on lifecycle analysis with high technology resolution (linked with the existing MIT energy-economic CGE models) that provides economic information and quantifies lifecycle GHG emissions, as well as impacts related to criteria pollutants and water.

2. Review of Existing Analytical Tools and Methods

This chapter provides a review of major energy modeling tools, their capabilities, scope, and features. We have synthetized our findings applicable to modeling tools based on the discussions during the ECW workshop. We would like to thank all the participants for their valuable insights on this project. We also developed a survey after the workshop and we appreciate those who provided detailed responses to our survey.

A variety of quantitative methods exist to examine possible future energy pathways under which decarbonization goals can be achieved and trade-offs for transformation identified. Table 1 provides a summary of a wide range of LCA and energy modeling tools developed by different organizations/institutions across the globe (citations to all models are provided in the References section). In our overview, we include integrated assessment models such as the Global Change Assessment Model (GCAM), which models the interaction between human and earth systems and the response of this system to global changes (GCAM, 2020) and MERGE-ETL: the Global Integrated Assessment Model, which accounts for linkages between economic activities and the energy sector (MERGE-ETL, 2020). It also includes a review of different impact category models such as the Soil and Water Assessment Tool (SWAT), the IMPACT World Water Tool, the Air Quality and Greenhouse Gases (GAINS) Model, and Model of Agricultural Production and its Impact on the Environment (MAgPIE). In addition to such modeling tools, this review gives insights about the current LCA databases, such as the Quebec Life Cycle Assessment inventory database and Global LCA Data Network (GLAD). Through collaboration with different institutes, we are examining which databases and models can be incorporated into SESAME. For example, the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) developed by the Stanford Environmental Assessment & Optimization Group is an LCA tool to measure the GHG emissions from the production, processing, and transport of crude petroleum (OPGEE, 2020). It is implemented in a user-accessible Microsoft Excel form and can be integrated into SESAME.

Table 1: Energy systems analysis tools and LCA databases.

<table>
<tr><th>Name</th><th>Institute</th><th>Format</th></tr>
<tr><td>Global Change Assessment Model (GCAM)</td><td>The joint Global Change Research Institute (University of Maryland and Pacific Northwest National Laboratory (PNNL))</td><td>• Available as open sources software
• Hosted on GitHub</td></tr>
<tr><td colspan="3">• Started in 1981 by PNNL.
• A dynamic-recursive model and a partial equilibrium model of the world with 32 regions
• Operates in 5-year time steps from 1990 to 2100
• An integrated global tool for assessing the interaction between human and earth systems and modeling the consequences and response of this system to global changes such as climate change.
• Models the behavior of and interaction across five systems including the energy system, water, agriculture and land use, economy, and the climate.
• Can be used to study climate change mitigation policies such as carbon tax and carbon trading.
• Explores the potential role of emerging energy supply technologies and the GHG consequences of specific policy measures or energy technology adoption including; CO_2 capture and storage, bioenergy, hydrogen systems, nuclear energy, renewable energy technology, and energy use technology in buildings, industry and the transportation sectors.
• A Representative Concentration Pathway (RCP)-class model→ it can be used to simulate scenarios, policies, and emission targets from various sources including the IPCC.
• Output includes projections of future energy supply and demand and the resulting GHG emissions, radiative forcing and climate effects of 16 GHGs, aerosols and short-lived species at 0.5×0.5 degree resolution, contingent on assumptions about future population, economy, technology, and climate mitigation policy.</td></tr>
<tr><td>The Soil and Water Assessment Tool (SWAT)</td><td>The joint Global Change Research Institute (University of Maryland and (PNNL))</td><td>• A public domain model
• A command-line executable file that runs text file inputs
• While user can set up inputs, there are provided interfaces to make it easier</td></tr>
<tr><td colspan="3">• Simulates the quality and quantity of both surface and ground water for a wide range of scales from small watershed to river basins.
• Has the capability to predict the environmental impact of land use, land management practices, and climate change.
• Assesses soil erosion prevention and control, non-point pollution control, and regional management in watersheds.</td></tr>
<tr><td>A Community Emissions Data System (CEDS) for Historical Emissions</td><td>The joint Global Change Research Institute (University of Maryland and (PNNL))</td><td>• Publicly available on GitHub repository
• Written in R and uses open-sources data.</td></tr>
<tr><td colspan="3">• Provides the annual estimates of historical global air emissions species from 1750 till present (over industrial era) for research and analysis.
• The users are able to add historical energy data for any country to let the system reflect historical energy consumption trends more accurately (has been used for the U.S., U.K., and Germany so far).
• The data system produces emissions estimates by country, sector, and fuel with the following characteristics:
    o Annual estimates of anthropogenic emissions (not including open burning) to latest full calendar year over the entire industrial era. Readily updated every year.</td></tr>
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Emission species: aerosol (BC, OC) and aerosol precursor and reactive compounds (SO_2, NO_x, NH_3, CH_4, CO, NMVOC) and CO_2 (as reference).
State/province spatial detail for large countries – in progress.
Seasonal cycle (monthly) and aggregate NMVOCs by sector/sub-sector.
Gridded emissions (up to 0.1°) w/ sub-national resolution for large countries.
Uncertainty estimated at the same level (country, fuel, sector) – in progress.

</td></tr>
<tr><td>GREET Model (The Greenhouse gasses, Regulated Emissions, and Energy use in Transportation Model)</td><td>Argonne National Lab</td><td>• Publicly available</td></tr>
<tr><td colspan="3">• An analytical tool that simulates the energy use and emissions output of various vehicle and fuel combination.</td></tr>
<tr><td>AWARE-US</td><td>Argonne National Lab</td><td>• Publicly available</td></tr>
<tr><td colspan="3">• Results of AWARE-US quantify the water stress and the impacts of increase in water consumption in various regions within the U.S.</td></tr>
<tr><td>The SET-Nav Project (Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation)</td><td>NTNU, E.U. Horizon 2020 programme</td><td>• Ongoing project</td></tr>
<tr><td colspan="3">• Started in April 2016.

• Being developed by European organizations, academic institutes as well as research and industry partners from Austria, Germany, Norway, Greece, France, Switzerland, the UK, France, Hungary, Spain and Belgium.

• The goal is to develop a model-based decision portfolio in the energy sector and analyze the impact of different future paths and policies as nations move towards a sustainable, efficient, and reliable energy system.</td></tr>
<tr><td>The INVADE Project</td><td>NTNU, E.U. Horizon 2020 programme</td><td>• Ongoing project</td></tr>
<tr><td colspan="3">• A flexibility management system using batteries that supports the distribution grid and electricity market while coping with grid limitations.</td></tr>
<tr><td>Global Gas Model (GGM)</td><td>NTNU</td><td>• Open access</td></tr>
<tr><td colspan="3">• A multi-period equilibrium model for analyzing the world natural gas market along the value chain from production wells to final consumers.

• The data set contains more than 90 countries thereby practically covering the entire global natural gas production and consumption. It also includes a detailed representation of cross-border pipeline, liquefaction, regasification, and storage capacities.</td></tr>
<tr><td>EMPIRE (European Model for Power System Investment with Renewable Energy)</td><td>NTNU</td><td>• Open access</td></tr>
<tr><td colspan="3">• A comprehensive power system model including generation, storage, and transmission capacity expansion.</td></tr>
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• Designed to determine optimal capacity investments under operational uncertainty, while also incorporating long- and short-term dynamics.		
REMES Model	NTNU	• Relevant publications are available.
• Computable General Equilibrium model that represents the Norwegian economy with a particular focus on the energy system. • Used to study the effects of macroeconomic policies on the Norwegian economy.		
Open input-output (IO)-Canada (Open source Input-output LCA model and tool to estimate lifecycle impacts of products and services)	Ecole Polytechnique Montreal	• free online access
• A Canadian environmentally extended IO model. • Based on Canadian economic input-output tables since 2009. • Can provide insights into the potential lifecycle impacts of the production and consumption of commodities in Canada. • Creates models that represent one's production facility or a specific product. • Conducts different types of contribution analysis for hot-spot assessment. • Is similar to other lifecycle inventory databases, with the difference that in Open IO-Canada, products are specified in terms of generic commodities and industry output and quantified in Canadian dollars rather than physical units.		
Quebec Life Cycle Assessment inventory database	Ecole Polytechnique Montreal	• Ongoing project
• The goal is to adapt Ecoinvent (the largest LCA database in the world) to the Quebec and Canadian context to facilitate LCA process for organizations, technologies, and services in Canada.		
The IMPACT world water tool	Ecole Polytechnique Montreal	• Publicly available
• A calculator that conducts lifecycle assessment of potential impacts associated with the use (consumption and/or degradation) of water. • Results of calculation will be as accurate as the provided data, which can go from specific watershed data to nation-wide data. • Minimum data necessary to run the calculations is the location where the system is and the volumes entering and leaving the product system.		
Swiss TIMES Energy system Model (STEM) for transition scenario analyses	• Paul Scherrer Institute	• Model description documents available
• Represented from resource supply to end-use energy service demands, such as space heating, mechanical processes, and personal/freight transport. • A long-time horizon (2010-2100) with an hourly representation of weekdays and weekends in three seasons. • Identifies the cost-effective combination of technologies and fuels to meet future energy service demands (given exogenously based on a set of scenario drivers), while meeting technical, environment, and policy constraints (e.g., CO_2 mitigation policies).		

<table>
<tr><td colspan="3">• The output includes technology investment and energy use across different sectors. These energy uses can be aggregated to report different indicators such as: primary energy supply, final energy consumption, seasonal/daily/hourly electricity demand and supply by technology type, CO_2 emissions, cost of energy supplies, and the marginal cost of energy and emissions commodities</td></tr>
<tr><td>European Swiss TIMES Electricity Model (EUSTEM)</td><td>Paul Scherrer Institute</td><td>• Ongoing project</td></tr>
<tr><td colspan="3">• Finds the most cost-effective combination of power plants and electricity generation mixes to meet exogenously given E.U. electricity demands.

• Can be used for long-term electricity supply scenario analysis.

• Includes 11 regions encompassing 20 of the 28 E.U. members states (pleas Switzerland and Norway)

• Has high temporal resolution and long model horizon from 2010 to 2070 with high intra-annual detail at seasonal and weekly levels to account for fluctuations in electricity supply and demand at an hourly time resolution.

• Covers 90% of the total installed capacity and 95% of the total electricity generation of EU-28. Each of the regions are connected though aggregated interconnectors, which enable electricity trade between regions based on long run marginal cost of electricity suppl.

• Is calibrated to the 2010 electricity statistics by including all existing power plants aggregated by plant type and fuel mix; and a wide range of new and emerging electricity generation technologies.

• For each of the region, renewable energy resource potential and carbon capture and storage (CCS) potentials are implemented. All input data and assumptions are well documented.</td></tr>
<tr><td>Global Multi-regional MARKAL (GMM) model</td><td>Paul Scherrer Institute</td><td>• Not available</td></tr>
<tr><td colspan="3">• Provides a long-term (2100) bottom-up representation of the global energy systems (disaggregated into 15 regions).

• Provides a detailed representation of energy supply technologies and aggregate representation of demand technologies.

• For each region, there are assumptions on the dynamics of technology characteristics, resource availability, and demand.</td></tr>
<tr><td>MERGE-ETL: Global integrated assessment model</td><td>Paul Scherrer Institute</td><td>• Model description documents available</td></tr>
<tr><td colspan="3">• An integrated assessment model combining a bottom-up description of the energy system disaggregated into electric and non-electric sectors, a top-down model based on a macroeconomic production function, and a simplified climate cycle.

• The integrated approach in MERGE-ETL accounts for linkages between economic activity and the energy sector, such that the model determines endogenously energy demands, prices, technology choice and economic output.

• Has been applied to explore uncertainty related to global climate and nuclear policies in the wake of the Fukushima disaster, focusing on the impact on Switzerland.</td></tr>
<tr><td>BEM (Bi-level electricity modeling)</td><td>Paul Scherrer Institute</td><td>• Model description documents available</td></tr>
<tr><td colspan="3">• Oligopolistic capacity expansion with subsequent market-bidding under transmission constraints.</td></tr>
<tr><td>Air Quality and Greenhouse Gases (The GAINS Model)</td><td>International Institute for Applied Systems Analysis</td><td>• Web-based with free access</td></tr>
</table>

<table>
<tr><td colspan="3">• Launched in 2006 as an extension to the RAINS model which is used to assess cost-effective response strategies for combating air pollution, such as fine particles and ground-level ozone.

• Provides an authoritative framework for assessing strategies that reduce emissions of multiple air pollutants and greenhouse gases at least costs, and minimize their negative effects on human health, ecosystems and climate change.

• Used for policy analyses. Scientists in many nations use GAINS as a tool to assess emission reduction potentials in their regions.

• Estimates historic emissions of 10 air pollutants and 6 GHGs for each country based on data from international energy and industrial statistics, emission inventories and on data supplied by countries themselves. It assesses emissions on a medium-term time horizon, with projections being specified in five-year intervals through the year 2050.

• Estimates for each country/region the potential emission reductions that are offered by about 2000 specific emission control measures and their costs.

Can be operated in two ways:

• In "scenario analysis" mode, it follows emission pathways from sources to impacts, providing estimates of regional costs and the environmental benefits of alternative emission control strategies.

• In "optimization" mode, it identifies where emissions can be reduced most cost-effectively. The model identifies a balance of concrete measures for different pollutants, sectors, and regions that achieve air quality and GHG reduction targets at least cost, considering the contributions of different pollutants to different air quality and climate problems.</td></tr>
<tr><td>OPGEE: The Oil Production Greenhouse Gas Emissions Estimator</td><td>Stanford, Environmental Assessment & Optimization Group</td><td>• Using public data sources where possible and being implemented in a user-accessible Microsoft Excel form</td></tr>
<tr><td colspan="3">• An engineering-based LCA tool for the measurement of GHG emissions from the production, processing, and transport of crude petroleum.

• The system boundary extends from initial exploration to the refinery entrance gate.</td></tr>
<tr><td>IMAGE: Integrated Model to Assess the Global Environment</td><td>PBL Netherlands Environmental Assessment Agency</td><td>• Models are not public. Some results and data are available.</td></tr>
<tr><td colspan="3">• An Integrated Model to assess the Global Environment.

• An ecological-environmental model framework that simulates the environmental consequences of human activities worldwide.

• It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being.

• The objective is to explore the long-term dynamics and impacts of global changes that result from interacting socio-economic and environmental factors.</td></tr>
<tr><td>Global Trade Analysis Project (Database and model)</td><td>Center for Global Trade Analysis</td><td>• Information and most resources on the GTAP website are available.</td></tr>
<tr><td colspan="3">• A global database describing bilateral trade patterns, production, consumption and intermediate use of commodities and services.

• A global model for an analysis of trade, agriculture and environmental policies.</td></tr>
<tr><td>The forest and agricultural sector optimization model (FASOM)</td><td>USDA</td><td>• Relevant publication is available.</td></tr>
</table>

<table>
<tr><td colspan="3">• A dynamic, nonlinear programming model of the forest and agricultural sectors in the U.S.

• Was initially developed to evaluate welfare and market impacts of alternative policies for sequestering carbon in trees but also has been applied to a wider range of forest and agricultural sector policy scenarios.</td></tr>
<tr><td>REMIND</td><td>Potsdam Institute for Climate Impact Research</td><td>• The source code may be copied for the sole purpose of reading.

• Operation of the model for research and commercial applications, distribution and any other use are not allowed.</td></tr>
<tr><td colspan="3">• A global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector.

• It solves for an inter-temporal Pareto optimum in economic and energy investments in the model regions, fully accounting for interregional trade in goods, energy carriers and emissions allowances.

• Allows for the analysis of technology options and policy proposals for climate mitigation.</td></tr>
<tr><td>Global LCA Data Network (GLAD)</td><td>UN Environment</td><td>• Publicly available
• Web based platform</td></tr>
<tr><td colspan="3">• Aims to achieve better data accessibility and interoperability. The network will be comprised of independently-operated LCA databases (nodes), providing users with an interface to find and access lifecycle inventory datasets from different providers.

• One of the main functionalities will be the conversion function which will allow users to convert a dataset from its native format in the source database (node) into another format convenient for the user.</td></tr>
<tr><td>Multiple Interface Life Cycle Assessment (MiLCA)</td><td>Sustainable Management Promotion Organization</td><td>• Available to purchase</td></tr>
<tr><td colspan="3">• A lifecycle assessment (LCA) support system including 3000 process datasets.</td></tr>
<tr><td>Global Emissions Model for integrated Systems (GEMIS)</td><td>International Institute for Sustainability Analysis and Strategy (IINAS)</td><td>• A public domain</td></tr>
<tr><td colspan="3">• A public domain lifecycle and material flow analysis model and database that IINAS provides freely.</td></tr>
<tr><td>Umberto LCA+</td><td>ifu Hamburg</td><td>• Available to purchase</td></tr>
<tr><td colspan="3">• LCA software solutions for product sustainability</td></tr>
<tr><td>Model of Agricultural Production and its Impact on the Environment (MAgPIE)</td><td>Potsdam Institute for Climate Impact Research</td><td>• Code available on GitHub</td></tr>
<tr><td colspan="3">• The objective function of the land use model is to minimize total cost of production for a given amount of regional food and bioenergy demand.</td></tr>
<tr><td>Integrated Database of the European Energy System (JRC-IDEES)</td><td>E.U. Commission</td><td>• Publicly available</td></tr>
<tr><td colspan="3">• Provides very detailed information on the energy system and its underlying drivers for all 28 E.U. Member States in annual time steps starting from the year 2000 up to 2015 in the current version.</td></tr>
</table>

SESAME is a novel, transparent, energy-system assessment tool, which enables an assessment of GHG emissions (and costs) from approximately 80% of the economy across various sectors such as power, road-transportation, industrial, and residential at both the pathway-level and system-level. The remaining 20% of economy sector that is not included in SESAME includes aviation, maritime, and any industries other than petrochemical, iron and steel, and cement. This makes SESAME a powerful tool for providing a multisector representation. To the best of our knowledge, no other publicly available tool has been previously developed to assess lifecycle emissions across the energy system. The system-level analysis by SESAME is enabled by the embedded power systems and vehicle fleet models that capture market dynamics and allow users to explore the dynamics of technology adoption and usage. SESAME incorporates the impacts of technological, operational, temporal, and geospatial characteristics of a pathway or system in its analysis. SESAME uses modeling results (as exogenous input) from an economy-wide scenario analysis model such as EPPA to perform future scenario analysis. EPPA informs SESAME regarding predictions for future electricity and energy mix, sectoral demand and supply, prices (e.g., fuels and electricity), regional differences, trade flows, and sectoral and regional emission profiles, among others. On the other hand, SESAME provides technology granularity that informs the parameterization of new technologies in EPPA. SESAME also provides information on the change in emissions coefficients over time for the aggregate sectors in EPPA. For example, as the fleet mix changes, SESAME can assess how the emissions associated with manufacturing vehicles changes. Such information can then inform the emissions coefficients EPPA uses for its aggregate sectors.

As data sources and LCA pathways are different across regions, the goal is to expand the scope of SESAME to make it usable globally. This selection will include a wide range of countries with different states of economic development (i.e., developed, rapidly developing, slowly developing). This economic state can influence the relevant policies in those regions, for example, regarding decarbonization or expanding renewable penetration. In addition, in selecting regions to include in SESAME, data availability would definitely be a challenge. Therefore, there needs to be collaboration with local institutions as well as regional partners and experts in order to collect the necessary data and expand the model. We initially started with the U.S. as the base case, since data availability made it an easier case to study. But as the next step, the goal is to investigate how the model can be adapted to other regions.

In expanding the scope of the model, another issue to consider is identifying the types of energy sources/carriers (e.g., hydro, solar, wind sources, hydrogen) that are available in selected regions. For example, hydrogen is becoming an important energy carrier in gas exporter countries and there are increasing questions regarding the role that hydrogen can play in a decarbonized energy system. Power-to-X (P2X) is also important to consider in the expanded version of SESAME, as many technology options are being discussed for P2X, especially stronger coupling with heating systems. Also, as countries are incorporating more and more fluctuating renewable energy, it becomes critical to provide system flexibility to avoid the loss of renewable energy and ensure power reliability. Therefore, demand side management and flexibility are significant in analyzing decarbonized energy systems to ensure resilient, secure, and optimal supply of energy.

The expanded version of SESAME will include techno-economic assessment capabilities to estimate all costs associated with the lifecycle of a product that are directly covered by one or more of the actors in the product lifecycle (e.g., supplier, producer, user/consumer, end-of-life actor). Lifecycle costing (LCC) in SESAME will connect the upstream to the end users—lifecycle costs from "Cradle to Grave." This methodology provides a sound combination of both the environmental and economic performance of a product to help with guiding technological development and managerial decisions in a more robust way. It also helps identify and optimize trade-offs between environmental and economic/business aspects.

We have developed a capacity expansion model called GenX at MIT, which was first used in the Future of Nuclear in a Carbon Constrained World study published in 2018 (the Future of Nuclear in a Carbon Constrained World, 2018). We have continued development of this model as part of the Future of Storage study underway at MITEI as well as other projects. Linking this capacity expansion model with SESAME is within the scope of this project to understand possible energy futures with a long-term perspective that predicts investments and energy transitions throughout decades. In order to capture the uncertainties that influence future energy transitions and choices such as ranges in techno-economic parameters of technologies, uncertainty in economic development and in resource availability, we will develop scenario analysis and robust optimization models to identify optimal decarbonization policies and future energy pathways.

3. Sustainable Energy Systems Analysis Modeling Environment (SESAME): Overview

Lifecycle Assessment (LCA) is a technique that addresses the environmental aspects and potential environmental impacts of a product throughout its lifecycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave) (ISO 1040, 2006), (Frischknecht et al., 2016). Traditionally, LCA has been used to assess a specific product throughout its lifecycle pathway, which can be called a pathway-level analysis. Software and tools such as openLCA (Ciroth, 2007), (Herrmann and Moltesen, 2015), SimaPro (Herrmann and Moltesen, 2015), (Simapro, 2019), GaBi (Thinkstep, 2019), GHGeneius (Stanciulescu and Fleming, 2006), (Squared Consultants Inc., 2019), and GREET (Wang, 1999) are designed to give users flexibility in conducting various pathway-level LCAs. To address the need for quantifying the decarbonization level of the energy sector, one needs to explore the overall GHG emissions across the energy system, which can be called a system-level analysis. We have developed a tool capable of both pathway-level and system-level lifecycle analysis, which we refer to the tool as SESAME (Sustainable Energy System Analysis Modelling Environment). The system-level analysis by SESAME is enabled by the embedded power systems and vehicle fleet models that capture market dynamics and allows the user to explore dynamics of technology adoption and usage. SESAME incorporates the impacts of technological, operational, temporal, and geospatial characteristics of a pathway or system in its analysis.

SESAME is built as a MATLAB application that encapsulates LCA codes (MATLAB files), lifecycle inventory databases (Excel and MATLAB files), and integrated process simulations (Aspen Plus Simulations). SESAME's modular framework constitutes the underlying analytical engine that covers the lifecycle steps of major energy conversion pathways. The first version of the tool contains more than 1300 individual pathways, which are responsible for ~80% of U.S. greenhouse gas (GHG) emissions. Detailed process simulation capabilities have been incorporated for in-depth analysis of the majority of conversion processes, such as power generation, biorefining, production of hydrogen, methanol, and dimethyl ether (DME). Although geographical applicability depends on Lifecycle Inventory data, the developed technology base is location agnostic. In the expanded version of SESAME, we will include other impact categories beyond global warming potential such as air pollutants and water footprint. Energy access, standard of living, and electrification rates in developing economies are undeniably among important impact categories, which are out of scope for SESAME.

Material and methods

LCA methodology, system boundaries, and functional units

To accurately represent the energy system, SESAME was developed as a pathway-level and system-level LCA tool following the ISO 14040 and 14044 standards (ISO 1040, 2006), (ISO 1044, 2006). SESAME is designed to conduct attributional LCA for all the pathways and systems that can be defined via the modular architecture of the tool. For select products, e.g., corn ethanol and corn stover ethanol, and select systems, e.g., power system, SESAME enables conducting consequential LCA. For biofuels, published data on consequential elements (e.g., land use change) projected by various economic models such as the Global Trade Analysis Project (GTAP), the Forestry and Agricultural Sector Optimization Model (FASOM), Food and Agricultural Policy Research Institute (FAPRI), and Global Change Assessment Model (GCAM), are pre-populated in the lifecycle inventory of SESAME. For the power system, we can model and project the GHG emissions as a consequence of renewables penetration in the grid. To our knowledge, there is no previous publication on the consequential LCA of a power system.

We have specified system boundaries for the LCA of all the products of focus in SESAME. The system boundaries encompass all the lifecycle steps (cradle-to-grave); these are upstream, midstream, process, CCUS as an optional step, gate to user, and end use.

Depending on the nature and function of the product, its functional unit could be different. For example, for biofuels, the functional unit could be one MJ of biofuel (calculated based on low heat value) or one mile driven by a car fueled by 100% biofuel. For power, the functional unit could be one MWh (consumed by a car or a residential facility) or one mile driven by an electric vehicle.

Modular tool architecture

SESAME is designed based on a matrix of modules comprising of six key vectors, each representing a lifecycle step: upstream, midstream, process, Carbon Capture, Utilization and Storage (CCUS), gate to user, and end use (Figure 4).

Modules are shown with dashed red boxes in Figure 4. They represent a set of common operations, and may have several sub-modules. Users select one module from each column. The collective selected modules by the users will form a pathway to produce a specific product (listed in the green box on the top right-side of Figure 4). Depending on the pathway, skipping columns or selecting multiple modules from the same column is also possible. The modular structure allows for creating numerous individual pathways to conduct pathway-level LCA. To conduct a system-level LCA, we can group as many modules/sub-modules as needed to represent a system (e.g., transportation system or power system). We can conduct the LCA of a transportation system by connecting each transportation fuel lifecycle sub-module to our vehicle fleet model.

The upstream module in Figure 4 represents extraction and production of feedstock, key minerals, and also chemicals that are necessary for subsequent conversion processes. Feedstocks can be fossil-based or renewable-based. Fossil feedstocks (and their major sub-modules) included in SESAME are natural gas (conventional, and shale gas), crude oil (conventional, tight oil, and oil sands), and coal (bituminous, sub-bituminous, lignite).

*Concentrated Solar Power, **Integrated Gasification Combined Cycle, ***Carbon Capture, Utilization & Storage

Figure 4 Modular representation of the energy system as defined in SESAME.

Renewable feedstock modules comprise biomass (corn, corn stover, forest residue, biogas), solar (photovoltaics, concentrated solar power), wind, hydropower, wave & tidal, and geothermal. The biomass upstream module contains production and harvesting related emissions. For other renewable modules, since there are no associated emissions during power generation step, all lifecycle emissions are included in their corresponding upstream modules. Depending on the resource, the impact of technology options, location, etc. are included as a variable.

The midstream module represents the transportation of energy feedstocks to the processing step based on the phase of the feedstock: gas, liquid, or solid. The gas midstream module includes processes (compression, separation, liquefaction, flaring) that can be applied to any gaseous feedstock, e.g., natural gas and biogas. Additionally, common gas transportation modes such as pipeline, tank, and shipping are included. Modules within the same lifecycle step can be stacked in case more than one module needs to be included for the operation. For example, in the case of a natural gas feedstock, a compression step will be required for almost any kind of transportation step; hence, the midstream step will include both compression and pipeline transportation. The liquid midstream module comprises separation and transportation via pipeline, rail, ship, and truck options. The solid midstream module contains various operations that are part of solids processing, such as drying, crushing/milling, and transportation via truck, ship, and rail. For nuclear power generation, uranium ore transportation is included in the solid module.

The process module represents one of the key lifecycle steps, in which Heat & Power and Industrial are the two main modules. All major thermal power generation options are represented as sub-modules such as sub-critical and super-critical steam turbines, gas turbine, combined cycle, and integrated gasification combined cycle. For heat supply options, steam generation and combustion are included. Nuclear power plants are also included in this step. The industrial module includes all major industrial processes. The Petroleum Refinery Lifecycle Inventory Model (PRELIM) (Abella & Bergerson, 2012), was used to develop the refining module with gasoline and diesel as primary products. Seventeen generic refinery configuration and three crude types (West Texas Sour, West Texas Intermediate, Venezuela Leona) are included as feedstocks. Ethanol production (from corn or corn stover) is covered in the biorefinery module. We use NREL's Aspen simulation for corn stover ethanol production. The gasification module is a general model to convert solid energy feedstocks to synthetic gas. Production of various fuels such as methanol, dimethyl ether (DME), hydrogen, and polyethylene chemicals are included within dedicated modules and assessed by using Aspen plus simulations. For polyethylene production, the polymerization reactor was simulated by using Aspen (not the rest of the process).

Technology options such as hydrogen production via steam methane reforming and auto-thermal reforming are defined as submodules. Natural gas stations for the production of compressed natural gas and liquefied natural gas are also included in the process step, although they do not involve a chemical conversion. Finally, heavy industry processes for iron and steel and cement modules are part of the process step.

We included CCUS as an optional lifecycle step. CO_2 capture, compression, utilization, and storage are represented with separate modules. Capture technologies include absorption, adsorption, and oxy-combustion options.

The gate to user module covers the transportation of products from the plant to the end user. The general structure is similar to the midstream step with a few differences, including addition of electricity transmissions, advanced energy storage options, and distribution of heat (steam).

The end use module includes the electric power, transportation, and industrial sectors. The electricity module can be a simple electricity demand function as well as connected to a power system model that represents hourly load profiles with changing generation mix. The heat module specifies heat demand and its temperature level. The liquid products module contains gasoline, diesel, methanol, ethanol, dimethyl ether (DME), Liquefied Petroleum Gas (LPG), and Liquefied Natural Gas (LNG). Gaseous products include Compressed Natural Gas (CNG) and hydrogen. Solid products in the model are cement, polyethylene, iron, and steel. In addition to products, a few variables are included under end-use modules, such as the adoption of different technologies for transportation, engine efficiency improvement, and process intensification in industry; these enable conducting sensitivity analyses. As a general rule emission allocation of co-products are done based on energy content and specified for cases that do not follow this rule. For all the LCAs conducted, we have checked the input assumptions to verify consistency among underlying assumptions.

One of the advantages of the modular design is that it allows layering regional variations with minimal intervention.

Modeling framework

SESAME's programming architecture is implemented in MATLAB by integration with Aspen Plus process simulation software using the methodology presented by (Gençer & Agrawal, 2017) and (Gençer et al., 2015). This approach allows complementing lifecycle analysis with process simulation capabilities to capture the performance and emission variations arising from technological, operational, and geospatial factors (by calculating energy and mass balances). This architecture provides a platform to implement simulations of process units with high emission rates, critical for system design. As shown in Figure 5(a), Excel, MATLAB, and Aspen plus are used to feed input assumptions to the MATLAB core script. As needed, the tool can be equipped with more programming platforms and connected to various existing tools. The lifecycle inventory for SESAME was developed by using publicly available, peer-reviewed data. The updated version of SESAME is currently implemented in Python and has a publicly available web version that can be found at: sesame.mit.edu.

A novel aspect of this analytical framework is the ability to assess key systems interactions and couplings. This allows transition options to be comprehensively assessed on an apples-to-apples basis. SESAME's modular design allows performing such comprehensive analyses; specifically, it can be evolved as the complex energy system restructures. Capabilities for integrating process simulations allows exploring the impact of operational and topological changes in the process. For the initial set of simulations, scaled-up processes consistent with industrial operation standards have been used. However, the platform allows users to integrate process simulations at different scales including lab-scale processes and perform a full assessment of these processes in different pathways and systems. This feature can be used to understand the GHG emission reduction potential of a novel process relative to conventional ones or to analyze a modification in process integration such as introduction of green hydrogen into an industrial facility.

The modular approach is composed of four main compartments at the highest level: User Input, Control Panel, Life Step Modules, and Output, as depicted in Figure 5(b). Users select from default options to initiate the computation. The control panel module constitutes the core of the tool that takes users inputs and communicates with relevant life step modules to send and receive information. The results from each life step module are adjusted and combined in accord with the user's selections. Finally, the results are reported as output in the desired form and units.

Results are presented in accordance with the functional unit of the pathway/system selected. For the pathways with energy products such as electricity and fuel, the output is per unit energy. For chemicals pathways, results are presented per unit mass; fuel results can also be presented per unit energy. For transportation pathways, the results are presented per distance driven; and for heavy duty transportation, the results are presented per distance-load driven. All the results can be presented at scale instead of per unit basis, and various units can be selected.

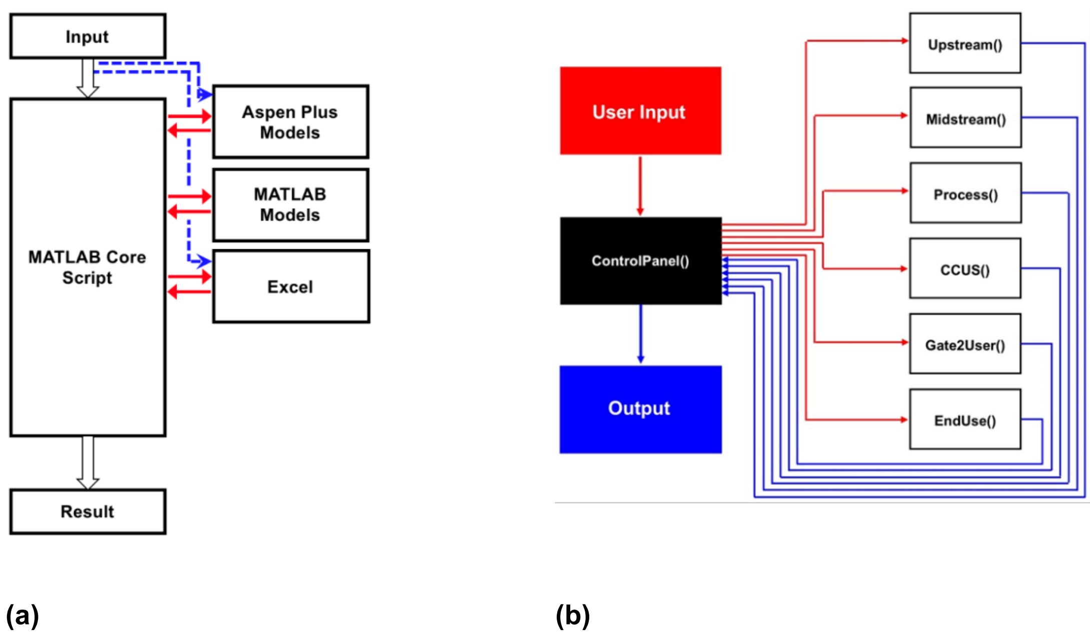

Figure 5 (a) The communication between the MATLAB Core Script and auxiliary components: MATLAB Models, Aspen Plus Models, and Excel models and databases are shown. **(b)** MATLAB is used to develop life step modules, each one of which has its unique structure. Each module is composed of numerous custom developed MATLAB functions. “Excel” refers to Excel models as well as databases.

Results and discussion

System-level LCA results: GHG emissions of the U.S. energy system

Using our system-level assessment methodology, we screened more than 80% of the GHG emissions in the U.S. energy system (in 2018). It was performed by calculating and summing up GHG emissions from all the modules (dashed red boxes in Figure 4) listed in each lifecycle step (dashed blue columns in Figure 4) using publicly available data from the U.S. EPA (U.S. EPA, 2018). Our results show that process and end use steps represent a significant fraction of overall GHG emissions from the U.S. energy system. Depending on the selected pathway, the process step could be the most GHG intensive such as in power generation from fossil fuel pathways; the power generation process is the highest GHG emitter among all lifecycle steps. For some other pathways, such as gasoline production from crude oil, the major GHG emitter is the end use (the vehicle tailpipe emissions). This high-level estimation demonstrates the emission hotspots in an overall pathway.

System-level LCA results: GHG emissions of the transportation sector

For a transportation case study, we estimated future GHG emissions from the U.S. passenger vehicle fleet, given car sales projections from the EIA (U.S. EIA, 2012). Figure 6(b) and (c) show that, even as the operating fleet grows ~15% from today to 2050, fleet GHG emissions decline by ~23%. This is due primarily to projected improvements in car fuel economies (increased MPGs) and the carbon intensity of electricity. Lower-carbon electricity means lower-carbon car production and EV operation. EIA's sales projections are shown in Figure 6(a). Car sales are a key input to SESAME's fleet emissions module. The module utilizes Argonne National Laboratory's VISION model (Sing et al., 2004), with several important adjustments, including: incorporation of car production emissions and computing fuel production emissions (what VISION labels "fuel carbon coefficients") from our LCAs of transportation fuels (gasoline, diesel, electricity, hydrogen, etc.). Car production is included because it is an important part of the vehicle travel lifecycle and contributes non-trivially to the emissions with respect to operation (~15% of total fleet emissions between today and 2050). In addition to car sales, other important inputs to the fleet emissions module include car fuel economies (MPGs) and a car lifetime distribution that assumes the average car lasts approximately 180,000 miles (FHWA, 2009). It should be emphasized that this example is provided to (a) demonstrate the analytical power of SESAME in converting fleet characteristics (such as EV market share) into resulting emissions.

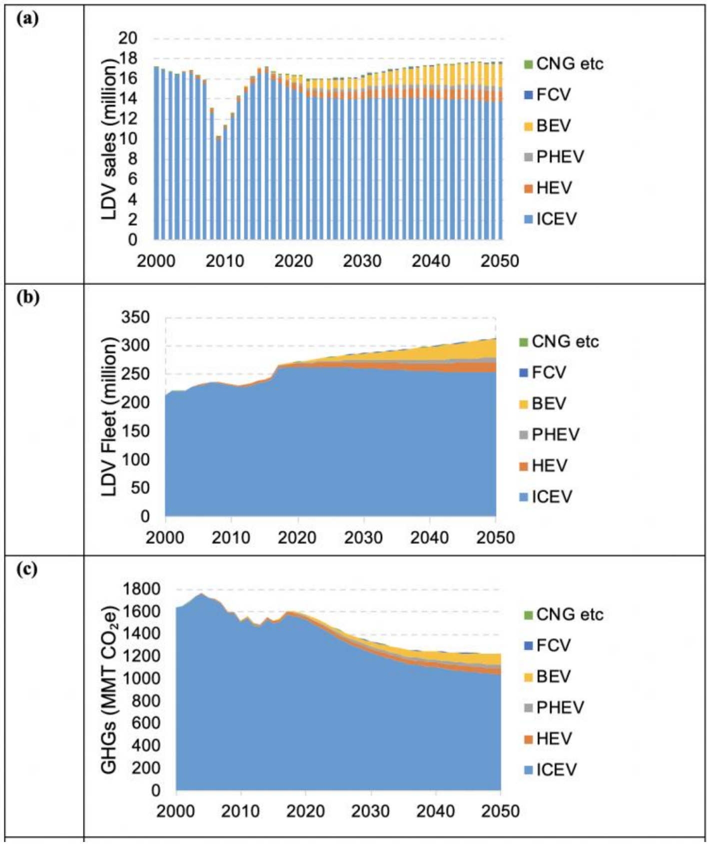

Figure 6 SESAME's vehicle fleet results for the EIA Outlook 2019 baseline case. (a) Passenger vehicle Sales (million), (b) Total LDV fleet (million), (c) GHG emissions (MMtons CO_{2e}) by car type.

<u>System-level LCA results: GHG emissions of the power sector</u>

To represent the electric power system, we have included historic hourly generation profiles of every fossil-fuel fired power generator with a nameplate capacity greater than 25 MW in the U.S. (U.S. EPA, 2018) from 2004-2017. SESAME's user interface allows users to display each unit's hourly load profiles and important statistics such as annual capacity factor and coefficient of variance of different power generation technologies. Additionally, hourly lifecycle analysis can be performed based on historic observations. As a case study, lifecycle emissions of generators in the US have been calculated using the embedded hourly generation profiles of thermal generation units. Results for a combined cycle gas turbine unit in California (El Segundo Power Plant Unit 5) are shown in Figure 7. The lower graph shows the hourly electricity generation and dots are the hourly calculated full lifecycle emissions in tCO_{2e}. For this particular unit, we observe more than 40% fluctuation in total emissions. While one reason for this change is the lower net generation, the other reason is higher emission intensity operation due to operation at off peak mode.

Figure 7 LCA Results at hourly resolution from El Segundo combined cycle power plant unit 5 is estimated using SESAME's power system database. The analysis is performed via the Power Grid Systems Analysis tab of the user interface.

<u>Pathway-level LCA results: Comparison of lifecycle carbon footprint of various transportation fuel options</u>

System-level transportation results, like those in Figure 6, are built upon pathway-level LCAs of different fuels and vehicle types. For each one of the transportation options many factors can be modified that will significantly impact the lifecycle GHG emissions, Figure 8 displays the results of diesel passenger vehicle emissions from three different crude oils (WTI: West Texas Intermediate, WTS: West Texas Sour, VenLeona: Venezuela Leona) processed in eleven refinery configurations.

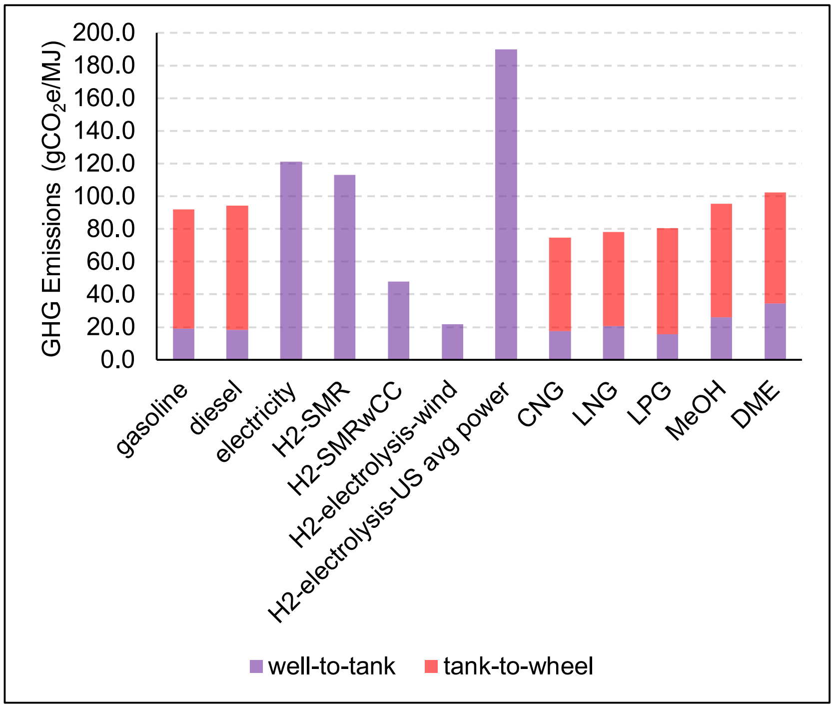

Figure 8 Fuel Cycle GHG Emissions. Electricity and H_2-electrolysis represent U.S. average power cases, assuming the 2018 U.S. grid mix with emission intensity of 437 gCO_2e/kWh. (Note: depending on the input assumptions, the LCA results will change.)

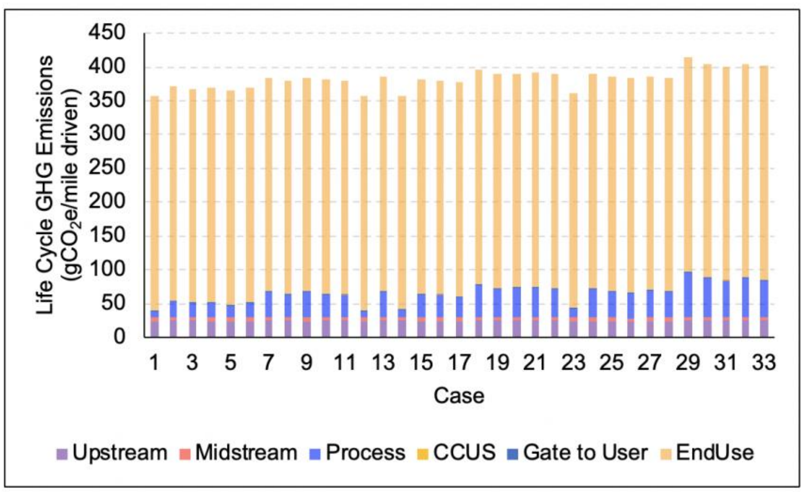

Figure 9 Well-to-wheel LCA GHG emissions (gCO_2e/mile driven) of various crude oil and refinery options included in SESAME for an average diesel light duty vehicle (fuel economy: 26.2 MPG).

Pathway-level LCA results: Comparison of lifecycle carbon footprint of various power sector options
Numerous combinations for power generation can be defined and their lifecycle emissions can be calculated in SESAME. We present in Figure 10 base case results for common fossil fuel-based power generation options, details of each case in the figure are listed in Table 2. In addition to technological variability, such as inclusion of various gas turbine models, capturing the impact of operation variation is very important.

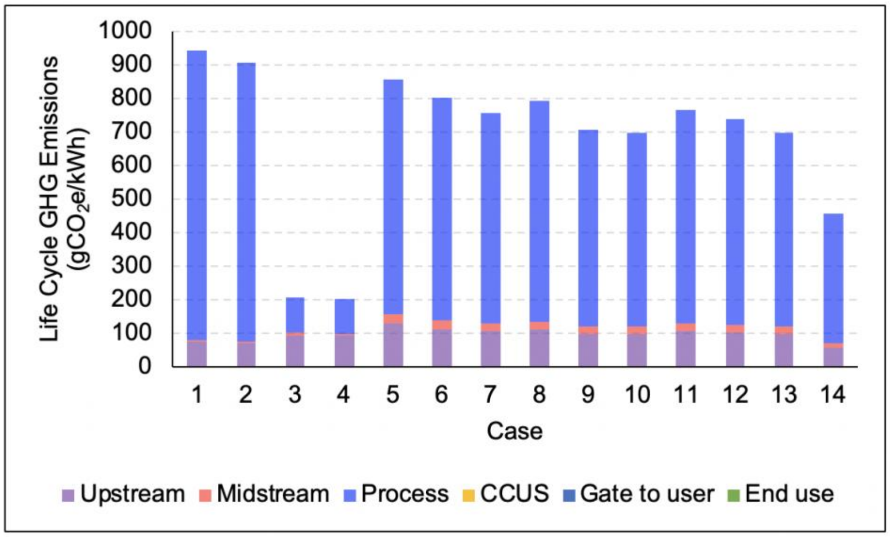

Figure 10 Summary of main power generation LCA results.

Table 2: Life stage components of power generation pathways shown in Figure 10 The default scenario was specified by using the average transportation mix in the U.S. (using data from GREET 2017). For CCUS cases, 90% CO_2 capture rate is assumed. Captured CO_2 is permanently stored in a geologic formation and is further utilized.

Case	Upstream	Midstream	Process	CCUS	Gate to User	End User
1	Coal	Default	Pow-Sub	No	Power dist	Electricity
2	Coal	Default	Pow-Sup	No	Power dist	Electricity
3	Coal	Default	Pow-Sub	Yes	Power dist	Electricity
4	Coal	Default	Pow-Sup	Yes	Power dist	Electricity
5	NG - Conventional	Default	Pow-GT-GE5371	No	Power dist	Electricity
6	NG - Conventional	Default	Pow-GT-GE6581	No	Power dist	Electricity
7	NG - Conventional	Default	Pow-GT-GE6101	No	Power dist	Electricity
8	NG - Conventional	Default	Pow-GT-GE7121	No	Power dist	Electricity
9	NG - Conventional	Default	Pow-GT-GE7241	No	Power dist	Electricity
10	NG - Conventional	Default	Pow-GT-GE7251	No	Power dist	Electricity
11	NG - Conventional	Default	Pow-GT-GE9171	No	Power dist	Electricity
12	NG - Conventional	Default	Pow-GT-GE9231	No	Power dist	Electricity
13	NG - Conventional	Default	Pow-GT-GE9351	No	Power dist	Electricity
14	NG - Conventional	Default	Pow-CC	No	Power dist	Electricity

Although emissions from renewable power generation are significantly lower than the fossil fuel-based alternatives, they are not zero. Hence, we have developed and implemented extensive analysis capabilities for solar and wind conversion technologies in SESAME. A snapshot of results is shown in Table 3. Details of these modules and analyses of solar PV (Miller et al., 2019), (Miller et al., 2019) and integration of energy storage technologies with solar PV and wind power systems (Miller et al., 2018) are available in the literature.

Table 3: Solar PV and wind power lifecycle GHG emissions for example cases.

Case	Tech	Location	Installation type	Life (yrs)	PV Efficiency (%)	Turbine maker	Lifecycle Emissions (gCO_{2e}/kWh)
1	PV, mc-Si	India SW	Utility scale, fixed-axis	30	16	N/A	37
2	PV, mc-Si	India SW	Utility scale, tracking	30	16	N/A	34
3	PV, sc-Si	China NE	Utility scale, fixed-axis	30	17	N/A	73
4	PV, sc-Si	China NE	Residential, rooftop	30	17	N/A	77
5	PV, CdTe	U.S. SW	Utility scale, tracking	30	15.6	N/A	14
6	PV, CdTe	U.S. NE	Utility scale, fixed	30	16.6	N/A	20
7	Wind	U.S. MW	Onshore	20	N/A	Vestas	7
8	Wind	Germany	Onshore	20	N/A	Siemens	5
9	Wind	U.S. NE	Offshore	15	N/A	Siemens	13
10	Wind	U.K. E	Offshore	30	N/A	Siemens	7

4. The Economic Projection and Policy Analysis (EPPA) Model: Overview

The MIT Economic Projection and Policy Analysis (EPPA) model is a multi-sector, multi-region computable general equilibrium (CGE) model of the global economy. It has been applied to a wide range of topics: policy impacts on the economy and emissions, comparison of different energy and environmental policy instruments, prospects for new technologies, agriculture and land use, and—in some versions—environmental feedbacks on the economy through human health and agricultural productivity (Chen et al., 2016). The model can be run in a standalone mode (e.g., Jacoby and Chen, 2014) to investigate the implications on economy, energy choices, and the resulting emissions; or it can be coupled with the MIT Earth System Model (MESM) to form the MIT Integrated Global System Modeling (IGSM) framework (e.g., Sokolov et al., 2009; Webster et al., 2012) to analyze climate implications of energy choices.

EPPA has become a family of models, with different versions developed from the core model to examine in detail specific sectors or technologies such as private vehicle alternatives (Karplus et al., 2013a, b; Ghandi and Paltsev, 2019; MIT, 2019), the economics of producing jet fuel from biofuels (Winchester et al., 2013), the health and economic effects of air pollution (Nam et al., 2013), or land-use change (Gurgel et al., 2007). Incorporating such additional features often requires substantial data development beyond the basic economic database. The latest version of the model (EPPA version 6) provides a platform to develop economic projections to evaluate the implications of energy and climate policies; moreover, it provides a robust platform for ongoing model development.

The EPPA model is regularly updated as new global economic data become available. The current version of the model has been designed to allow focus on broader global change topics including land-use change, agriculture, water, energy, air pollution, transportation, population, and development. General equilibrium models are well-suited to the broader focus because they represent all sectors of the economy and interactions among sectors. In addition to a theoretically grounded general equilibrium representation of the world economy, the model represents physical details on resources (different types of land and fossil fuels) and the environmental implications of their use.

CGE modeling has been widely used in various economy-wide analyses such as trade liberalization effects, interaction between foreign direct investment (FDI) and trade, optimal taxation, modeling for roles of power sector technologies, and energy and environmental policies (Bovenberg and Goulder, 1996; Rutherford et al., 1997; Tapia-Ahumada et al., 2015; van der Mensbrugghe, 2010; Zhou and Latorre, 2014). The EPPA model combines the strengths of the traditional CGE approach with advanced features, including explicit advanced energy conversion technologies, land use change, and accounting of both greenhouse gas and conventional pollutant emissions. It is a multi-region and multi-sector recursive dynamic model of the world economy solved at 5-year intervals from 2010 through 2100. The current version of the model includes 18 regions and 14 sectors, with labor, capital, and multiple energy resources as primary factors. The model represents economic activities of three types of agents in each region: producers, consumers, and government. Solving the model recursively means that production, consumption, savings, and investment are determined by current period prices. Savings supply funds for investment, and investment plus capital remaining from previous periods forms the capital for the next period's production (Chen et al, 2016).

The main economic database used in the EPPA model is the Global Trade Analysis Project (GTAP) dataset (Narayanan et al., 2012). The model is updated based on the latest releases of the GTAP dataset and calibrated to the historic energy use based on the IEA World Energy Outlooks and IMF World Economic Outlooks. The EPPA model also includes non-CO_2 GHG emissions and urban pollutant emissions. The non-CO_2 GHGs included in the model are methane (CH_4), perfluorocarbon (PFC), sulfur hexafluoride (SF_6), and hydrofluorocarbon (HFC); the urban pollutants considered are carbon monoxide (CO), volatile organic compound (VOC), nitric oxide and nitrogen dioxide (NO_x), sulfur dioxide (SO_2), black carbon (BC), organic carbon (OC), and ammonia (NH_3). Most of the base year non-CO_2 GHGs and urban pollutants are drawn from the Emissions Database for Global Atmospheric Research (EDGAR) Version 5 (Crippa, et al., 2019). For later years, energy use levels are determined endogenously by factors such as the patterns of economic growth, technological change (both energy productivity growth and price-driven), and relevant energy or emissions policies.

Illustrative examples: Model simulations

GDP, energy use, and emissions

To illustrate the policy application of the EPPA model, we consider a greenhouse gas mitigation policy consistent with the goal of keeping an increase in global average surface temperature below 2°C relative to pre-industrial levels. The Intergovernmental Panel on Climate Change (IPCC) has set forth a carbon budget that approximates, on a century time scale, allowable cumulative emissions that, at median climate response, is associated with 2°C warming (IPCC, 2014a). A path through 2100 consistent with that budget is shown in Figure 11.

Identical percentage reduction caps (from 2015 emissions levels) in each region are imposed. The sample policy starts from 2020, cutting CO_2 emissions to 50% of 2015 level by 2050. Other, non-CO_2 GHGs, are taxed at the same GWP-equivalent (IPCC, 2014b), endogenously determined, regional carbon prices resulting from these caps. The sample policy imposed here is not meant to reflect political feasibility. It simply allows us to examine the model performance under an ambitious GHG target that is the stated goal of international negotiations. The simulation results on global GDP are presented in Figure 12, which shows that the sample policy would induce a reduction in global GDP by 2050 of about $14.5 trillion (from about $177.8 to $163.1 trillion). The cost over the considered time horizon is a reduction of 3.0% in net present value terms compared to Business-as-Usual (BAU) Scenario, assuming a 5% discount rate. A caveat for the exercise is that simulations for policy impact, by nature, may vary due to factors such as the uncertainties in BAU long-term productivity growth (which in turns affects the economic growth), technology advancement, etc. (Chen, 2015).

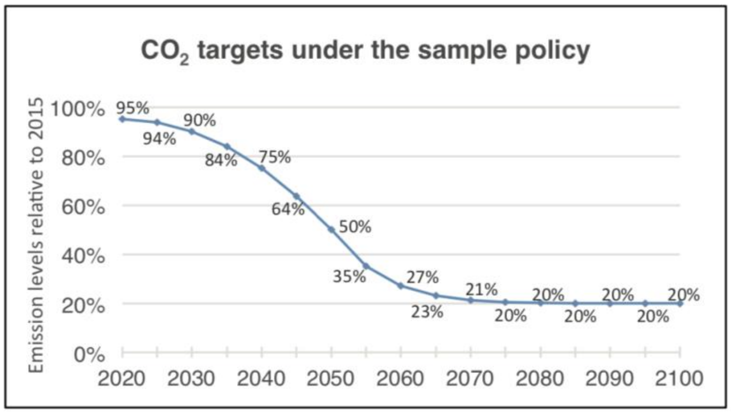

Figure 11 CO_2 targets under the sample policy.

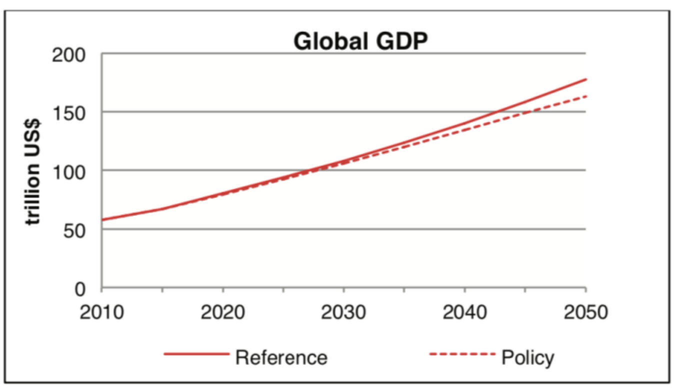

Figure 12 Global GDP: BAU vs. Policy.

Since energy use patterns are closely related to emissions, model outputs are presented for total primary energy demand (TPED) levels in Figure 13a (for the BAU case) and Figure 13b (for the policy case). For the BAU simulation, compared to the 2010 level, the global GDP level is tripled (from around $57.6 trillion to $177.8 trillion in 2007 U.S. dollars) by 2050. The global TPED increases at a much slower pace by 80.1% (from 497.7 EJ in 2010 to 896.1 EJ in 2050) due to energy efficiency improvements and changes in industrial structure. Nevertheless, the projection shows that the global economy during the same period will continue to rely heavily on fossil fuels with an increasing share of gas (23.6% to 25.4%), while the shares of coal (28.7% to 28.3%) and oil (33.8% to 34.2%) remain almost unchanged. Under this scenario, the roles of hydro, biofuels, other renewables (wind and solar), and nuclear power do not change much over time.

With the sample policy, results shown in Figure 13b suggest that a large cut in fossil fuels consumption is needed to achieve the policy goal (from 428.3 EJ in 2010 to 317.7 EJ in 2050). Under this scenario, as expected, the roles of hydro, biofuels, and other renewables become more important, with the sum of shares rising from about 8.7% in 2010 to 24.0% in 2050. Additionally, the share of nuclear power also increases, from around 5.2% in 2010 to 9.0% in 2050.

Figure 14 presents the energy-related CO_2 emissions (global GHG emissions have similar trajectories in these scenarios). In the BAU scenario, compared to the 2010 levels, the emissions increase by 82.7% by 2050, which is directly related to the consumption of fossil fuels that increases by 84.0% during the same period. The slightly slower growth path of the emissions is a result of the slight increase in the share of gas, as discussed previously. With the sample policy, the emission level will be cut by almost 70% relative to the reference level in 2050.

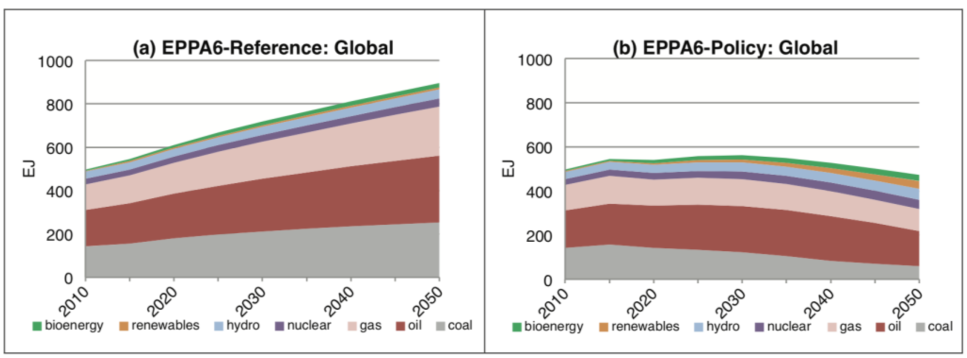

Figure 13 Total primary energy demand: (a) BAU vs. (b) Policy.

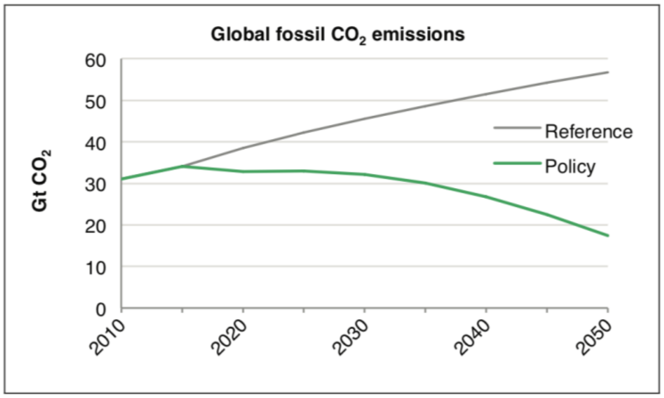

Figure 14 Global fossil CO_2 emissions.

Representing technological details

In this section (based on Morris et al., 2019), we provide an illustration of the level of technological detail that is needed to calibrate a representation of technologies in the EPPA model. Using an example of calculating levelized cost of electricity (LCOE) generation, we explain how the costs of technologies relative to an average wholesale electricity price are determined. These relative costs (that we call as *markups*) are important for deployment of advanced technologies in different regions of the model, because they determine competitiveness of different technological options. Similar calculations are performed for other categories of technologies, such as different types of private vehicles (battery electric, plug-in hybrid, internal combustion vehicles) and different options in the hard-to-abate sectors.

We start with an example of the LCOE and the resulting markup calculations for the U.S. We then show the regional variation in the markups. While we show the markup calculations for a particular year (2015 in our example), in energy-economic models the prices of all inputs to power generation change from time-period to time-period. Based on new prices, the resulting markups will be determined by the model depending on the new economic conditions. These new relative costs will determine the economic competitiveness and deployment of different technologies. Energy-economic models use a particular year (called a base year) as a starting year for which input data is collected. Our calculations for 2015 can be converted into the values for the base year of a given model.

The *markup* is the measure of the cost of a technology (including transmission and distribution costs as well as backup costs for intermittent technologies and carbon dioxide transportation and storage cost components for CCS technologies) relative to the average wholesale electricity price. The markup does not include government interventions, such as subsidies, renewable portfolio standards or feed-in tariffs. In order for the costs of such policies to be captured, these interventions should be explicitly represented in the model rather than in the markups.

The markup calculation for the U.S. is shown in Table 4 for more established technologies: new pulverized coal (denoted thereafter as “Coal”), natural gas combined cycle (“Gas”), biomass-fueled plant (“Biomass”), onshore wind for small and medium penetration levels (“Wind”), solar photovoltaic (“Solar”) and advanced nuclear (“Nuclear”). Wind and Solar are non-dispatchable technologies, i.e. they are not accompanied by back-up capacity, and can therefore contribute only a limited share to the total generation mix.

Table 4 shows the corresponding calculations for advanced technologies: new pulverized coal with carbon capture and storage (“Coal with CCS”), natural gas with CCS (“Gas with CCS”), biomass with CCS (“BECCS”), co-firing of coal and biomass combined with CCS (“Coal+Bio CCS”), advanced CCS on natural gas (“Gas with Advanced CCS”), wind (for large penetration levels) with natural gas turbine-based backup (“WindGas”), and wind (for large penetration levels) with biomass -based backup (“WindBio”). The Coal+Bio CCS technology assumes that coal is co-fired with 7.6% biomass (on a heat input basis), which is the amount of biomass calculated as necessary to offset the uncaptured coal emissions and therefore make the technology have net zero emissions. The gas with advanced CCS technology assumes 100% of CO_2 emissions are captured at low cost. This technology is at an early stage of development, and we base our representation on the NET Power technology. WindGas and WindBio are wind with either a gas turbine or a biomass-based backup with the default assumption that 1-for-1 backup capacity is required.

The relative value of an amount of money in one year is different when compared to another year (e.g., one tonne of coal will have a different cost when measured in 2005 dollars versus in 2015 dollars), therefore, it is important to represent the monetary values in the same units. While most of the cost data are from 2015 and 2017, all values in Tables 4 and 5 (and subsequent tables) are reported in 2015 U.S. dollars (USD).

We base our input cost values on IEA (2015) when possible. IEA (2015) provides a median, minimum, and maximum globally averaged value for key cost inputs. We use the median values for our base markups, but also use the minimum and maximum values to provide a range of markup values. Regional capital scalars, along with regional fuel and electricity prices, are used to make the calculations region-specific. We also assume the markups are for the Nth-of-a-kind for each technology. The details of calculations of the values in Tables 4 and 5 are provided in Appendix.

Table 4: Markup calculation for the U.S. for established power generation technologies (in 2015$).

		Units	Coal	Gas	Biomass	Wind	Solar	Nuclear
[1]	"Overnight" Capital Cost	$/kW	2148	1031	4181	1845	1581	4286
[2]	SCALED Overnight Capital Cost	$/kW	2365	1135	4602	2031	1740	4718
[3]	**Total Capital Requirement**	**$/kW**	**2743**	**1226**	**5339**	**2194**	**1879**	**6133**
[4]	Capital Recovery Charge Rate	%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
[5]	Fixed O&M	$/kW/year	39	30	109	50	26	71
[6]	Variable O&M	$/kWh	0.0035	0.0028	0.0054	0.0147	0.0168	0.0035
[7]	Project Life	years	20	20	20	20	20	20
[8]	Capacity Factor	%	85%	85%	80%	35%	20%	85%
[9]	(Capacity Factor Wind)							
[10]	(Capacity Factor Biomass/NGCC)							
[11]	Operating Hours	hours/year	7446	7446	7008	3066	1752	7446
[12]	Capital Recovery Required	$/kWh	0.0389	0.0174	0.0805	0.0756	0.1133	0.0870
[13]	Fixed O&M Recovery Required	$/kWh	0.0052	0.0041	0.0155	0.0165	0.0146	0.0095
[14]	Efficiency, HHV	%	42%	53%	30%			33%
[15]	Heat Rate, HHV	MJ/kWh	8.63	6.76	12.00	0	0	11.06
[16]	Fuel Cost	$/GJ	2.08	4.16	3.14	0.00	0.00	0.87
[17]	Fuel Cost per kWh	$/kWh	0.0179	0.0281	0.0377	0.0000	0.0000	0.0096
[18]	**Levelized Cost of Electricity**	**$/kWh**	**0.0656**	**0.0523**	**0.1391**	**0.1068**	**0.1447**	**0.1097**
[19]	Transmission and Distribution	$/kWh	0.03	0.03	0.03	0.03	0.03	0.03
[20]	**Levelized Cost of Electricity incl. T&D**	**$/kWh**	**0.0956**	**0.0823**	**0.1691**	**0.1368**	**0.1747**	**0.1397**
[21]	EPPA Base Year Elec Price	$/kWh	0.0924	0.0924	0.0924	0.0924	0.0924	0.0924
[22]	**Markup Over Base Elec Price**		**1.03**	**0.89**	**1.83**	**1.48**	**1.89**	**1.51**

Table 5. Markup calculation for the U.S. for advanced power generation technologies (in 2015$)

		Units	Coal with CCS	Gas with CCS	BECCS	Coal+Bio CCS	Gas with Advanced CCS	WindGas	WindBio
[1]	"Overnight" Capital Cost	$/kW	4100		8867			2536	6026
[2]	SCALED Overnight Capital Cost	$/kW	4514		9762			2792	6634
[3]	**Total Capital Requirement**	**$/kW**	**5417**	**2336**	**11714**	**5630**	**1431**	**3015**	**7165**
[4]	Capital Recovery Charge Rate	%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
[5]	Fixed O&M	$/kW/year	62	59	169	78	35	58	159
[6]	Variable O&M	$/kWh	0.0057	0.0065	0.0087	0.0057	0.0028	0.0141	0.0132
[7]	Project Life	years	20	20	20	20	20	20	20
[8]	Capacity Factor	%	85%	85%	80%	85%	85%	42%	42%
[9]	(Capacity Factor Wind)							35%	35%
[10]	(Capacity Factor Biomass/NGCC)							7%	7%
[11]	Operating Hours	hours/year	7446	7446	7008	7446	7446	3679.2	3679.2
[12]	Capital Recovery Required	$/kWh	0.0769	0.0332	0.1766	0.0799	0.0203	0.0866	0.2058
[13]	Fixed O&M Recovery Required	$/kWh	0.0084	0.0079	0.0242	0.0104	0.0048	0.0157	0.0433
[14]	Efficiency, HHV	%	33%	45%	21%	32%	53%	40%	30%
[15]	Heat Rate, HHV	MJ/kWh	10.92	8.02	17.35	11.14	6.77	9.02	12.00
[16]	Fuel Cost	$/GJ	2.08	4.16	3.14	2.08	4.16	4.16	3.14
[17]	Fuel Cost per kWh	$/kWh	0.0227	0.0333	0.0544	0.0243	0.0281	0.0031	0.0033
[18]	**Levelized Cost of Electricity**	**$/kWh**	**0.1230**	**0.0845**	**0.2783**	**0.1298**	**0.0594**	**0.1194**	**0.2655**
[19]	Transmission and Distribution	$/kWh	0.03	0.03	0.03	0.03	0.03	0.04	0.04
[20]	**Levelized Cost of Electricity incl. T&D**	**$/kWh**	**0.15**	**0.11**	**0.31**	**0.16**	**0.09**	**0.16**	**0.31**
[21]	EPPA Base Year Elec Price	$/kWh	0.09	0.09	0.09	0.09	0.09	0.09	0.09
[22]	**Markup Over Base Elec Price**		**1.66**	**1.24**	**3.34**	**1.73**	**0.97**	**1.73**	**3.31**
	For CCS								
[23]	Carbon Content	kgC/GJ	24.686	13.700	24.975	24.686	13.700		
[24]	Carbon Emissions	kgC/kWh	0.2696	0.1098	0.4333	0.2750	0.0928		
[25]	Carbon Dioxide Emissions	kgCO2/kWh	0.9886	0.4027	1.5887	1.0082	0.3401		
[26]	Percent Emissions Captured	%	95%	90%	90%	95%	100%		
[27]	CO2 Emissions Captured	kgCO2/kWh	0.9392	0.3624	1.4298	0.9578	0.3401		
[28]	Cost of CO2 T&S	$/tCO2	10	10	10	10	10		
[29]	CO2 Transportation and Storage Cost	$/KWh	0.0094	0.0036	0.0143	0.0096	0.0034		

In order to incorporate the costs related to intermittency, we add backup capacity. We consider two technological options for the backup power: natural gas turbine and biomass-based generation. The backup allows the combined technological option (intermittent generator and backup need not be located together geographically) to be considered dispatchable. Given the finding by Gunturu and Schlosser (2015), we assume 1-for-1 backup, with the backup operating 7% of the time. Since wind turbines are assumed to operate 35% of the time, this gives wind power with backup a combined capacity factor of 42%. For wind with backup technologies, we take the overnight capital cost for wind and add to it either the overnight capital cost for a gas turbine or for a biomass plant. The corresponding procedure is done for fixed O&M. For variable O&M, we combine the wind variable O&M and the backup variable O&M based on the capacity factor of the respective technologies relative to the combined capacity factor, e.g., 35/42 * (wind variable O&M) + 7/42 * (backup variable O&M). We assume that wind with backup technologies require an additional $0.01/kWh in transmission and distribution costs compared to other technologies.

In the United States, the lowest cost generation technology is gas with a markup of 0.89. The low markup for gas is due to its relatively low capital costs, short construction time, low fuel cost, and low fixed and variable O&M costs. The markup for wind generation (without any backup requirement) in U.S. is 1.48. At this markup, wind would be competitive with nuclear, but more expensive than gas with CCS technologies. However, at penetration levels requiring backup, the markup for WindGas rises to 1.73 and the markup for WindBio rises to 3.31, making WindGas competitive with coal with CCS.

Regional LCOE and markup values

The same procedure is followed for each region of the world represented in the EPPA model (see Figure 15 for the list of the regions). In each region, fuel costs and capital costs vary, as well as the average price of electricity (see Table 6). The resulting markups that show the relative competitiveness of electricity generation technologies therefore also vary.

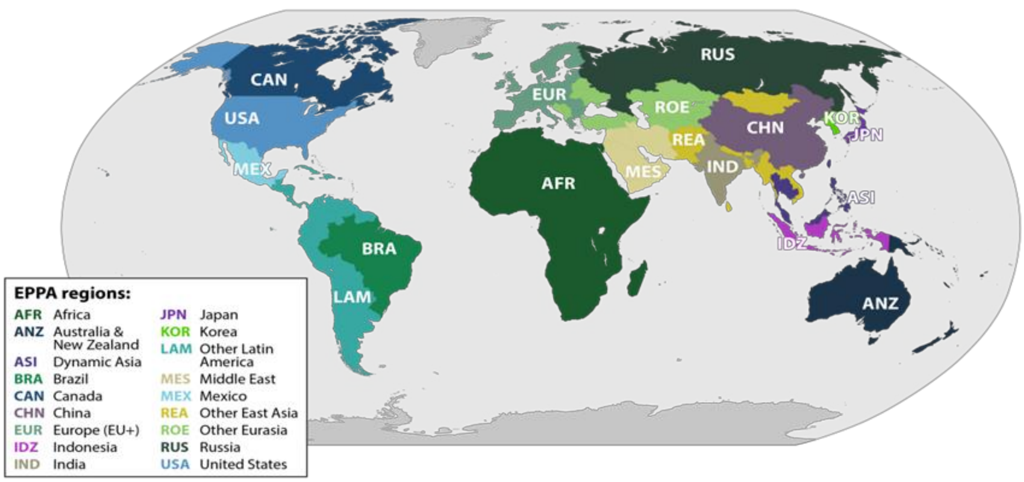

Figure 15 Regional representation in the EPPA model.

Figure 16 compares the markups for a set of technologies in major regions of the world. The minimum and maximum markups are used to show a range of markup costs, with the median markups represented by the black lines. China, where electricity prices are low, tends to have higher markups than other regions across technologies. However, the low capital costs in China bring the markups for more capital-intensive technologies (like Nuclear and Solar) closer to parity with other regions. Regions with high electricity prices, like Japan and Europe, consistently have the lowest markups across technologies compared to other regions. It is easier for advanced technologies to compete in regions where the electricity price is already high. Differences in regional electricity prices underscore the caution needed when comparing the absolute values of LCOE or markups between different regions. Technologies with low LCOE may still be expensive compared the electricity price in the region.

Table 6: Regional variation in prices and capital scalars.

	Electricity $/kWh	Coal $/GJ	Gas $/GJ	Biomass $/GJ	Capital Scalar
AFR	0.064	1.26	4.31	2.70	0.58
ANZ	0.101	2.38	5.32	2.75	1.21
ASI	0.078	2.35	6.17	3.08	0.42
BRA	0.106	2.85	3.79	2.53	1.09
CAN	0.073	1.98	5.17	2.72	1.44
CHN	0.051	1.51	6.96	3.79	0.33
EUR	0.139	2.61	7.11	3.03	1.42
IDZ	0.073	1.71	4.39	3.08	0.33
IND	0.089	1.33	6.04	5.75	0.79
JPN	0.146	2.64	6.76	10.29	1.23
KOR	0.080	2.41	8.22	3.08	0.62
LAM	0.090	2.44	1.88	2.70	1.09
MES	0.089	2.43	3.39	4.38	0.33
MEX	0.096	2.25	5.72	3.55	0.44
REA	0.106	2.16	5.19	3.53	0.87
ROE	0.092	2.47	6.11	3.25	0.67
RUS	0.032	1.59	4.21	2.68	0.33
USA	0.090	2.02	4.04	3.05	1.10

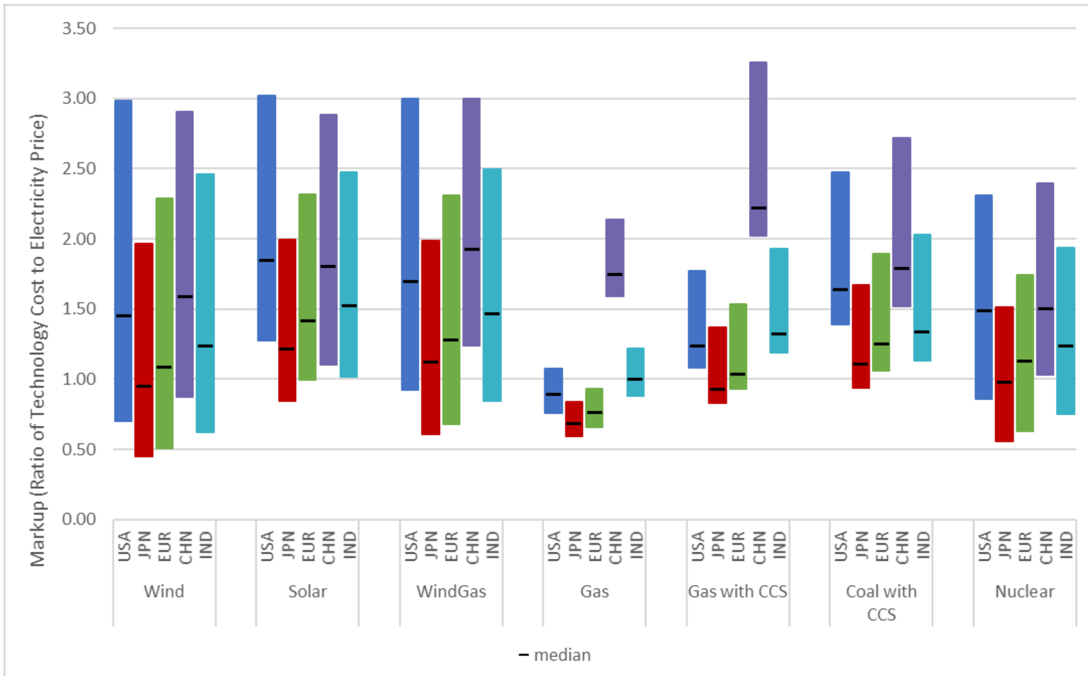

Figure 16 Markup range and median for a set of technologies in major regions. The colored bars represent the range using min and max data from IEA (2015), with the black line representing the median, which is used as the base markup. Markup values above 1 mean the cost of electricity generation from the technology is more expensive than the average wholesale electricity price.

5. Integration of SESAME and EPPA Models: Example from the Mobility of the Future Study

While each modeling approach has its strong sides (e.g., granular representation of technological options in SESAME, price responsiveness and sectoral linkages in EPPA), these approaches also have some shortcomings (e.g., limited representation of capital evolution in SESAME and low technology resolution in EPPA).

We aim to bring together the two strong modeling tools described above—SESAME and EPPA: A modular LCA tool (SESAME) that can perform pathway- and system-level analysis and an integrated assessment model (EPPA) that performs economy-wide analysis.

The combination of SESAME and EPPA tools can quantify lifecycle GHG emissions and their impacts, criteria pollutants impacts, water impacts, land impacts, socioeconomic impacts, and health impacts. For example, based on emission profiles and epidemiological relationships, the EPPA model estimates health impacts of air pollution on labor productivity, required health services, and GDP (Nam et al., 2010; Dimanchev et al., 2019). To quantify the footprints of criteria pollutants and water, we augment SESAME's platform and develop an extended SESAME model. For economy-wide scenario analysis, we use the modeling results from our EPPA model to inform the technology assessment platform as an exogenous input to SESAME. We design an extended SESAME model to be a publicly available technology option and scenario analysis tool that can use input information from any economy-wide system (or use the default settings that represent our base values). An example of SESAME and EPPA integration is provided below.

Mobility of the Future study

In the U.S. today, greenhouse gas emissions per mile for BEVs (battery electric vehicles) are approximately 55% of emissions per mile for a similarly sized ICEVs (internal combustion engine vehicles) on average (MIT, 2019). Per-mile greenhouse gas emissions for HEVs, PHEVs, and FCEVs (hybrid electric, plugin hybrid electric, and fuel cell electric vehicles) are all approximately 72%–73% of emissions from ICEVs. These comparisons are for similarly sized vehicles. In the case of BEVs and FCEVs, greenhouse gas emissions come mainly from the production of electricity and hydrogen, respectively; by contrast, most ICEV and HEV emissions come from the combustion of fuel on board the vehicle. Emissions associated with vehicle manufacture, including the manufacture of batteries, vary substantially across powertrains, but these differences are generally dwarfed by greenhouse gas emissions from the fuel lifecycle. However, the relative contribution from vehicle production becomes more substantial as the fuels used to operate different vehicles become less carbon intensive.

Current emissions for vehicles with different powertrains

Using SESAME, we estimate emissions per mile for vehicles with different powertrains based on current parameters for electricity and hydrogen generation and transmission in the U.S. (Figure 17). Figure 17 shows that BEV emissions per mile are approximately 55% the emissions of comparable ICEVs. Increased emissions from battery and fuel production are more than offset by increased powertrain efficiency, such that total fuel-cycle emissions per mile are lower for BEVs. Second, hybrid vehicle emissions per mile fall between ICEV and BEV emissions. Finally, emissions per mile for hydrogen FCEVs are approximately the same as for hybrid vehicles.

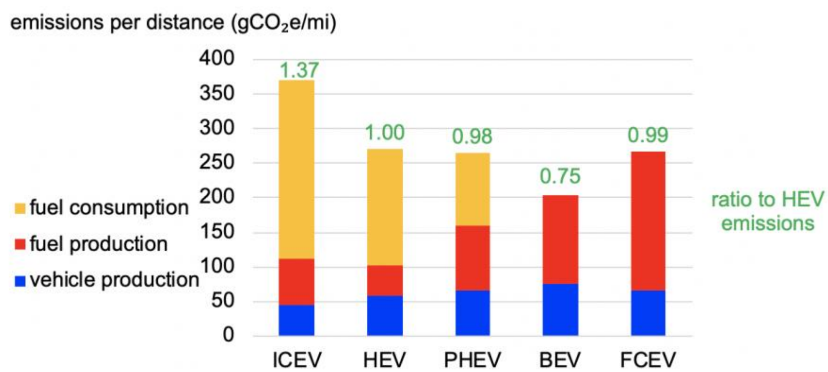

Figure 17 Lifecycle GHG emissions per mile for mid-size sedans with different powertrains, U.S. 2018 (note: depending on the input assumptions, the LCA results will change.)[1].

The results presented in the following sections are a product of combining the strengths of SESAME and EPPA model, where EPPA provided to SESAME the pathways for energy and electricity mix (by technology type) in different scenarios and SESAME provided to EPPA granular information about the different vehicle options (Figure 18). Such analysis and flow of information between SESAME and EPPA models is a case study for transportation sector but it can be applied to other sectors as well.

[1] Based on 180,000-mile life for all powertrains; U.S. 2018 average grid carbon intensity of 436 gCO_{2e}/kWh; gasoline production emissions of 19 gCO_{2e}/MJ; MPG values are 34 for ICEV, 52 for HEV, 42 gasoline and 110 electric for PHEV, 114 for BEV, 68 for FCEV (U.S. EPA 2018); 50/50 split of miles by gasoline and electric modes for PHEV; hydrogen production based on steam methane reforming with 13.6 gCO_{2e}/gH_2.

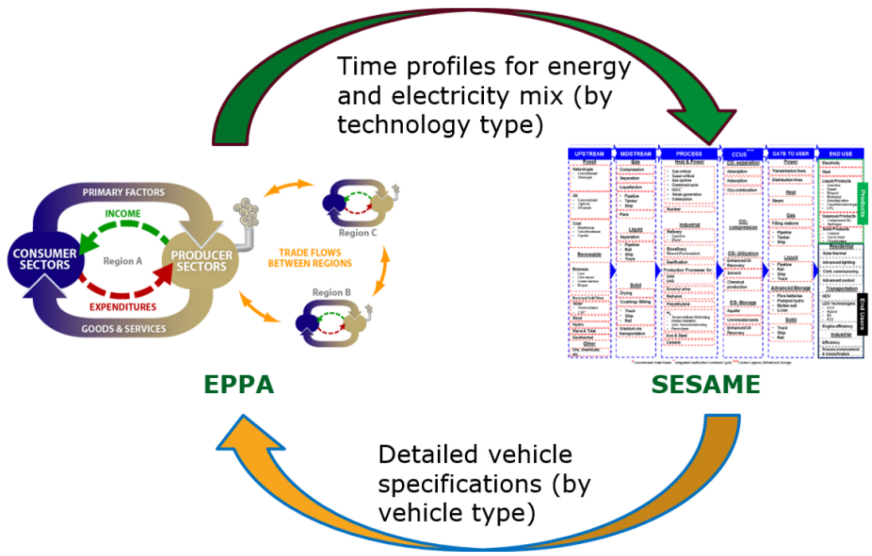

Figure 18 Illustrative diagram of information flows between EPPA and SESAME for an analysis of personal mobility. Similar flows can be established for other sectors.

<u>Projections of future emissions</u>

Given the sensitivity of BEV emissions to grid carbon intensity and the likelihood that grid carbon intensity will keep declining, one might expect the environmental advantages of BEVs over HEVs to increase over time. Put another way, it seems reasonable to expect that the ratio of BEV-to-HEV emissions will decline in the future. However, our analysis indicates that for scenarios where the grid's carbon intensity declines by less than 50%, the anticipated rate of MPG improvements for HEVs published in the literature will roughly keep pace with the rate of grid decarbonization. Figure 19 plots greenhouse emissions per mile for three powertrains using MPG projections from three different sources: MIT (Heywood and MacKenzie, 2015), the National Research Council (2013), and the National Petroleum Council (2012). All scenarios in the figure assume the same 34% decline in the average carbon intensity of the U.S. grid (from 436 gCO_{2e}/kWh in 2018 to 290 gCO_{2e}/kWh in 2050), based on a reference climate policy scenario.

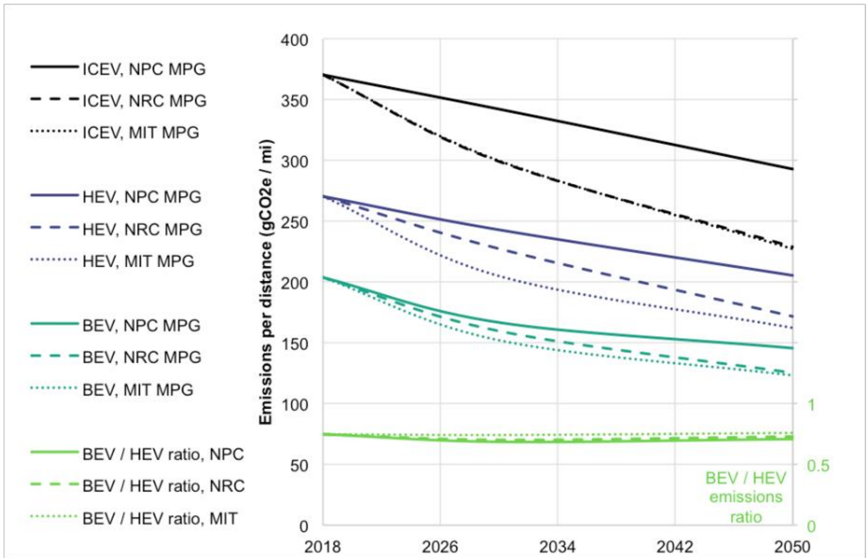

Figure 19 Vehicle emissions in the U.S. given different MPG projections.

Depending on MPG assumptions, the BEV-to-HEV emissions ratio (green curves) is projected to change from 0.75 to 0.71 between 2018 and 2050 (using the NPC values), from 0.75 to 0.76 (using the MIT values), and from 0.75 to 0.73 (using the NRC values). In other words, none of the three MPG projections shows a significant increase in the carbon advantage of BEVs relative to HEVs over the next 30 years. If we were to assume no change in vehicle MPG, a 34% reduction in grid carbon intensity would lower the ratio of BEV-to-HEV emissions from 0.75 to 0.57. However, the green lines in Figure 19 show that projected changes in MPG counter this grid decarbonization effect.

The rate of decarbonization in the electric power sector is an important unknown that will be driven by policy, technology, and economics. Figure 20 shows projected greenhouse gas emissions per mile for the three types of powertrains under three scenarios for grid evolution taken from the EPPA model. In the Reference scenario, the carbon intensity of the U.S. grid is assumed to fall 34% from 2018 to 2050, from 436 gCO_{2e}/kWh to 290 gCO_{2e}/kWh. In the Paris to 2°C scenario, the assumed decline is 47%; whereas in the Low-Cost Renewables scenario, the assumed decline is 92%. All plotted scenarios use the MIT projections for MPG gains by 2050 (Heywood and MacKenzie 2015): a 73% increase for ICEVs, a 90% increase for HEVs, and a 47% increase for BEVs. As discussed earlier, emissions from ICEVs and HEVs are not sensitive to the carbon intensity of the power mix, because most of their emissions come from fuel combustion in the vehicle. BEV emissions, on the other hand, are sensitive to the makeup of the power mix, as shown by the dotted blue curve. A 92% decline in grid carbon intensity would overwhelm projected MPG effects, such that the BEV-to-HEV emissions ratio would drop by approximately half by 2050 (from 0.75 to 0.37). In other words, a dramatic reduction in grid carbon intensity would indeed give BEVs a much larger CO_2 emissions advantage over HEVs.

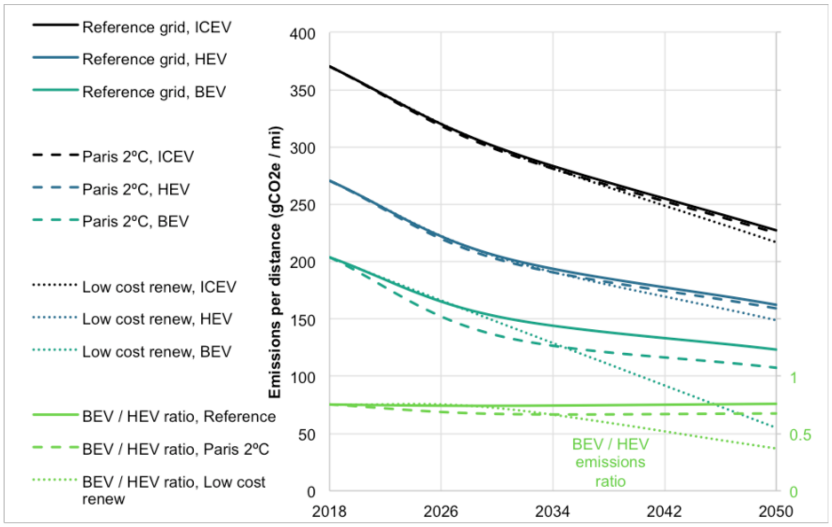

Figure 20 Vehicle emissions in the U.S. given different power grid projections.

Compared to other vehicle types, BEV emissions are much more sensitive to the carbon intensity of the power grid. As a result, BEV emissions show much greater geographic variation. For example, a BEV manufactured and charged with U.S.-average electricity would have 25% lower emissions than a comparable HEV, whereas a BEV manufactured and charged with China-average electricity would have 13% higher greenhouse gas emissions than a comparable HEV. These results reflect large differences in the carbon intensity of the power mix between these two countries.

Due mainly to projected reductions in grid carbon intensity and increases in MPG, greenhouse gas emissions from all types of vehicles are projected to decline over the next three decades (to 2050): by 30%–47% for BEVs, by 20%–40% for ICEVs, and by 25%–40% for HEVs. If the carbon intensity of the U.S. grid declines by less than 50% by 2050, the CO_2 emissions benefits of BEVs relative to ICEVs and HEVs will likely not increase significantly, due to changes in other factors including relative MPG. On average in the U.S., BEVs would likely continue to emit roughly 70%–75% of the greenhouse gases emitted by similar-sized HEVs on a per-mile basis, even as emissions from both declined on an absolute basis. If, on the other hand, grid carbon intensity declines dramatically, by 92% from 2018 to 2050, BEV emissions would decline from roughly 75% to 37% of HEV emissions.

Lifecycle greenhouse gas emissions from BEVs and FCEVs are highly sensitive to the carbon intensity of the electricity and hydrogen used to power these vehicles. We explored this sensitivity by considering lifecycle emissions based on the carbon intensity of electricity and hydrogen production today and based on some possible production pathways in the future. At present, a BEV operating on the most carbon-intensive state-level power mix in the U.S. can emit 22% more CO_2 than a comparable HEV. If the same BEV runs on electricity from the least carbon-intensive state-level power mix, on the other hand, its emissions performance can be about 63% better than a comparable HEV. A FCEV that runs on hydrogen generated via steam methane reforming has roughly the same lifecycle emissions as a comparable HEV, but these emissions could be reduced by about 44% if steam methane reforming is combined with carbon capture; alternatively, FCEV emissions could be 61% lower than for a comparable HEV if hydrogen is produced by electrolysis solely from wind power (or from other similarly low-carbon electricity). In stark contrast, FCEV emissions would be 45% higher if hydrogen is produced via electrolysis using electricity with the carbon intensity of the current U.S.-average power mix. Therefore, any programs that promote the adoption of advanced vehicle powertrains for purposes of climate change mitigation should be undertaken in concert with corresponding efforts to decarbonize the supply of electricity and hydrogen. In other words, the justification for deploying alternative powertrains is not based on the electricity and hydrogen supply as it exists today; rather, it is coupled to a vision and program of decarbonization that extends beyond the transportation sector alone.

Information for the different vehicle types was used in the EPPA model to explore three policy scenarios: (1)) a *Reference* scenario, which assumes no additional policies are enacted to mitigate greenhouse gas emissions and which excludes commitments associated with the Paris Agreement, (2) a *Paris Forever* scenario, which assumes implementation of commitments under the Paris Agreement by 2030 and continuation of those policies thereafter, but no additional policy action; and (3) a *Paris to 2°C* scenario, which assumes policy action beyond current Paris commitments to ensure that the increase in Earth's average surface temperature (relative to pre-industrial levels) does not exceed 2°C.

In the Mobility of the Future study (MIT, 2019) we found that meeting the ambitious climate-change mitigation targets will require substantial greenhouse gas emissions reductions across all sectors of the global economy, including personal transportation. A realistic path to decarbonizing light duty vehicle travel will require strategies that combine the task of reducing emissions with the objectives of improving personal mobility and supporting economic growth. Our modeling analysis is designed to find the pathways that maximize welfare subject to the specific emissions, resource, and budget constraints of different countries and regions.

Below we summarize the major findings from the EPPA model obtained for the Mobility of the Future study, where we envision a substantial electrification of private transportation. We project that the global EV fleet will grow from approximately 3 million vehicles in 2017, to about 95–105 million EVs by 2030, and 585–823 million EVs by 2050. At this level of market penetration, EVs would constitute one-third to one-half of the overall LDV fleet by 2050 in different scenarios, with the stricter carbon constraints implied in the Paris to 2°C scenario leading to the largest EV share. Our modeling suggests that EV uptake will vary across regions. China, the U.S., and Europe remains the largest markets in our study timeframe, but EV presence is projected to grow in all regions.

Figure 21 summarizes the impact of climate scenarios modeled here on several major output measures in 2050, relative to a 2015 baseline. EVs play a role in reducing oil use, but a more substantial reduction in oil consumption comes from economy-wide carbon pricing. Absent more aggressive efforts to reduce carbon emissions, global oil consumption is not radically reduced in the next several decades because of increased demand from other sectors, such as for heavy-duty transport and non-fuel uses. The figure indicates that global oil consumption does decline—by roughly 25% compared to the reference case—in the Paris to 2°C scenario, but only about 20% of this reduction is due to light-duty vehicle electrification.

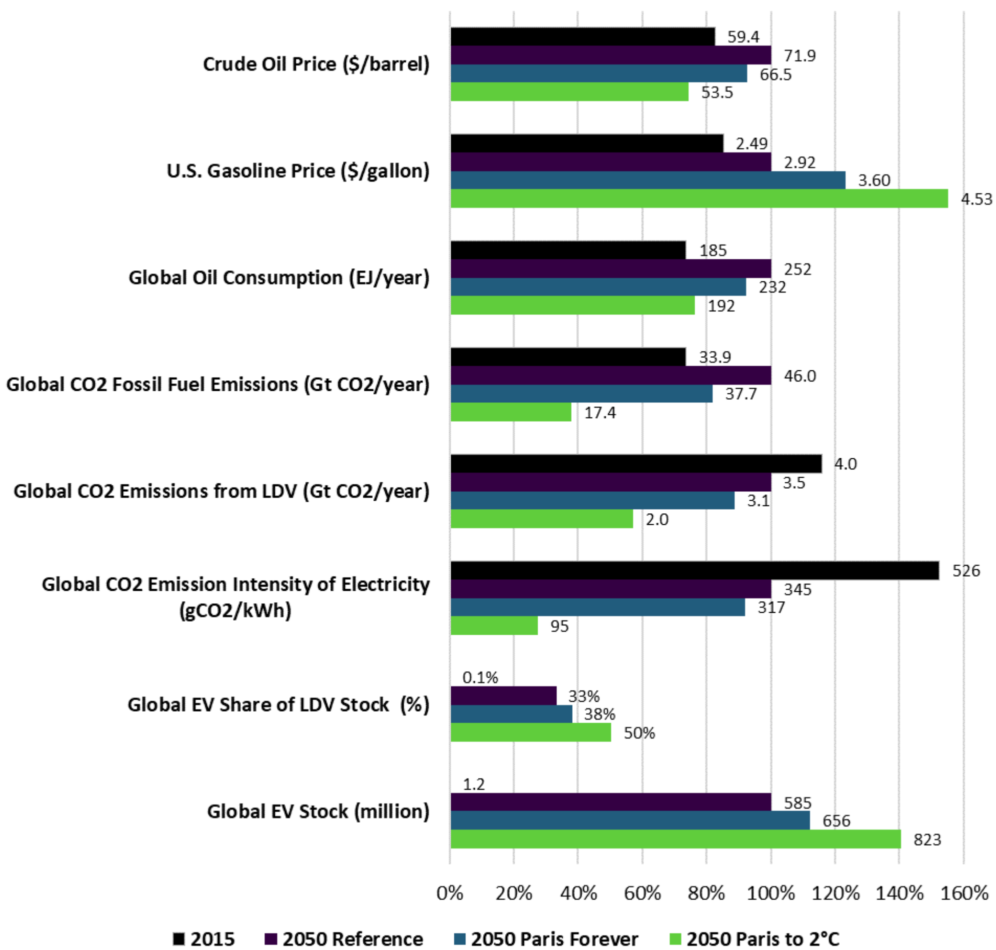

Figure 21 Major impacts of modeled climate scenarios in 2050 (2015 values are provided as reference).

In the Paris to 2°C scenario, global energy-related CO_2 emissions in 2050 are 62% lower than in the Reference scenario. Although 2050 CO_2 emissions from LDVs are 43% lower in the Paris to 2°C scenario than in the Reference scenario, this reduction in LDV emissions accounts for only 5% of the total difference in emissions, from all sources, between the scenarios. This reflects two realities: first, as a share of global carbon emissions, LDVs are a smaller contributor (12% of total emissions in 2015) than electricity generation (38% of total emissions); second, decarbonizing the electricity sector is generally less expensive than decarbonizing transportation. Since the economics of decarbonization favor greater reductions in the electricity sector, the LDV share of total carbon emissions in the Paris to 2°C scenario in 2050 is actually higher than the LDV share of total carbon emissions in the Reference scenario.

The very substantial emissions reductions demanded by the Paris to 2°C scenario require a confluence of many factors, including electrification of about 50% of the LDV fleet and significant decarbonization of electricity production (sufficient to achieve a 72% reduction in carbon intensity of the global power mix).

We estimate that the macroeconomic costs of the climate policies considered here range from a GDP loss of about 1.1% to 3.3% in 2050, relative to the Reference scenario. While these losses represent a substantial amount of money ($1–$3 trillion), they are equal in magnitude to one to two years of economic growth. It is important to keep in mind that our calculations do not account for the benefits (or avoided costs) of mitigating climate change, which could also be very substantial. The global economy expands from 2015 to 2050 in all scenarios, but growth is slower in the Paris Forever and Paris to 2°C scenarios. This obviously affects overall economic activity, with implications for global oil consumption and LDV fleet size.

We project that EVs will constitute a substantial share of the light-duty fleet by mid-century, regardless of climate policy. However, carbon policies will affect the speed of penetration and ultimate number of EVs on the road over the next few decades. As noted previously, climate impacts of EV deployment depend on progress toward decarbonizing the electric grid. Accordingly, policies to support EVs should go hand-in-hand with policies to support low-carbon electricity generation. Hydrogen-based FCEVs offer another pathway for decarbonization, but their potential within the mid-century timeframe depends on substantial cost reductions in terms of both vehicles and fuel production and distribution infrastructure.

Overall, we find that EVs, along with more efficient ICEVs and HEVs, represent a viable opportunity among a set of options for reducing global carbon emissions at a manageable cost. Support for further research and development (R&D) to advance these and other low-carbon transportation options will allow for the attainment of more ambitious decarbonization targets. The ultimate goal of mitigating climate change requires actions from all economic sectors, and efforts to address the contribution from personal transportation should be part of an integrated policy response to maximize human welfare, manage climate risks, and secure a foundation for sustainable economic growth and development in the future. For additional results from the SESAME and EPPA models, see MIT (2019).

Questions and Answers:

Q: How do these efforts fit into the ongoing energy transitions?

A: Recognizing that there are a multitude of possible energy transition pathways toward a low-carbon future with reliable and affordable clean energy, the International Energy Agency and MIT are working to combine the efforts of governments, academia, stakeholder experts, and industries towards the development of technologies to help address the policy and regulatory considerations associated with future energy development scenarios.

Q: What is SESAME?

A: SESAME—the Sustainable Energy Systems Analysis Modeling Environment—is a comprehensive system-level and pathway-level lifecycle assessment model. An expanded version of SESAME is being developed to quantify the footprints of criteria air pollutants and water. SESAME is built in a modular format, and it simultaneously covers various sectors and their interconnections, such as road transportation, power, industrial, and residential sectors.

Q: What do you mean by Lifecycle Analysis?

A: Lifecycle Assessment (LCA) is a technique that addresses the environmental aspects and potential environmental impacts of a product throughout its lifecycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave). Examples of cradle-to-grave elements are extraction, transportation, processing, disposal, and reclamation.

Q: What is the "Integrated Assessment Model?"

A: The Integrated Assessment Model (IAM) consists of the economy-wide, multi-sector, multi-region model (The MIT Economic Projection and Policy Analysis (EPPA) model) and the Earth system component of the Integrated Global System Modeling (IGSM) framework. EPPA is used for economy wide scenario analysis. The EPPA model is regularly updated as new global economic data become available.

Q: What does "system-level" and "pathway-level" mean?

A: To address the need for quantifying the decarbonization level of the energy sector, one needs to explore the overall GHG emissions across the energy system, which is a system-level analysis (includes the power, building, industrial, and transportation sectors; i.e., across sectors). A novel aspect of this analytical framework is the ability to assess key systems interactions and couplings. This allows transition options to be comprehensively assessed on an "apples-to-apples" basis. "Pathway-level" refers to the individual energy pathways. The SESAME framework covers more than 1000 energy conversion pathways.

Q: What energy types are covered?
A: Solar, wind, hydro, conventional oil and gas, unconventional oil and gas, coal, nuclear, and biomass.

Q: How do these tools fit with International Standards?
A: SESAME was developed as a pathway-level and system-level LCA tool following the ISO 14040 and 14044 standards (ISO 1040, 2006), (ISO 1044, 2006).

Q: Which other universities are working with MIT on these efforts?
A: Collaborations are being developed based on case studies and available datasets that other academic institutes can provide.

Q: Can these models link to models created elsewhere?
A: Yes. SESAME is constructed as a matrix of modules. Outputs from other models can serve as input to the SESAME workflow.

Q: Is carbon capture included in the models?
A: Yes. CO_2 capture, compression, utilization, and storage are represented with separate modules. Capture technologies include absorption, adsorption, and oxy-combustion options.

Q: How do these tools help policy makers?
A: The tool will help policy makers evaluate options, impacts, and national energy choices when exploring the impacts of relevant technological, operational, temporal, and geospatial characteristics of the evolving energy system. It helps them understand the lifecycle and economic and financial implications for GHG emissions, as well as impacts related to criteria pollutants, water, land, habitat, socioeconomic, and health, among others.

Q: What are the impact categories and measures?
A: Current impact categories are social, economic, environment, and national energy security; others can be added. Current measures are air, water, habitat, standard of living, gender equality, social, and health; others can be added.

Q: What will the Lifecycle Analysis Model focus on?
A: LCA models seek to represent the physical supply chain of multiple one-product pathways. They are important tools for assessment of material balances and environmental impacts (in physical terms) incurred during the cycle of production-consumption/disposal. LCA quantifies a product's

environmental impacts through input-output accounting of cradle-to-grave or cradle-to-gate processes.

Q: What is the primary use of the analytical framework?
A: The analytical framework will be applied to National Choice cases in the 2020-2022 time frame.

Q: Why are these tools being developed?
A: Low-carbon transformation of the energy system requires a combination of technology and policy options to ensure reliable, affordable, and clean energy. An assessment of plausible transition pathways can be guided with a set of tools that cover multi-sector dynamics of transitions and consider economy-wide and sectoral lifecycle analysis of numerous options. Economy-wide; and in particular, computable general equilibrium (CGE) models; offer a powerful analytic tool to analyze energy and climate policies and technology options and to tailor them to avoid potentially burdensome consequences for the economy.

Q: Will these models be publicly available?
A: Yes. The expanded SESAME version will be a publicly available technology options and scenario analysis tool that can use input from any economy wide system.

Q: Will the models be kept up-to-date?
A: Yes, SESAME's modular design allows for it to evolve as the complex energy system restructures.

Q: Does SESAME use proprietary data?
A: No, all the inputs to the tool are public. There are no proprietary data or proprietary process configurations embedded in the tool.

Q: What are Computable General Equilibrium (CGE) models?
A: CGE models provide an economic/financial lifecycle assessment of production-consumption flows. CGE models divide the overall economy into a detailed set of economic agents, which interact through markets. Some agents represent producing sectors, some are household groups, and some are governments. Each agent is represented by a validated behavioral model, including relevant constraints on its budget. The agents interact through markets for goods, services, labor, and capital. These models are described as general equilibrium because they simultaneously solve for all outcomes in all all sectors of the economy.

Glossary

BC: Black Carbon

OC: Organic Carbon

SO_2: Sulfur Dioxide

NO_x: Nitrogen Oxides

NH_3: Ammonia

CH_4: Methane

CO: Carbon Monoxide

CO_2: Carbon Dioxide

NMVOC: Non-methane volatile organic compound

GHG: Greenhouse Gas

SDG: Sustainable Development Goals

LCA: Lifecycle Assessment

IAMs: Integrated Assessment Models

CGE: Computable General Equilibrium

IEA: International Energy Agency

CCUS: Carbon Capture, Utilization, and Storage

DME: Dimethyl Ether

LPG: Liquefied Petroleum Gas

LNG: Liquefied Natural Gas

CNG: Compressed Natural Gas

HEV: Hybrid Electric Vehicle

PHEV: Plugged-in Electric Vehicle

BEV: Battery Electric Vehicle

FCEV: Fuel Cell Electric Vehicle

LDV: Light-Duty Vehicle

PFC: Perfluorocarbon

SF6: Sulfur Hexafluoride

HFC: Hydrofluorocarbon

IPCC: Intergovernmental Panel on Climate Change

GDP: Gross Domestic Product

LCOE: Levelized Cost of Electricity

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Furthermore, this collaborative program brings together leading experts from academia, national governments, and industry to dialogue on robust science-based methodologies for evaluation of plausible energy futures and improved understanding of potential policy impacts on these futures.

This manuscript was further enhanced through a technical workshop in Paris in October 2019, hosted by organized by MITEI and the IEA. Academic experts from several universities and research institutions, as well as members from IEA and companies in the energy, transportation, and power sectors exchanged views and ideas on the best modeling approaches for energy systems.

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Marie-France Benassy	Total S.A.
Pedro Crespo del Granado	PNNL/NTNU
Fabrice Devaux	Total S.A.
Jae Edmonds	PNNL
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Karl D. Fennesey	ConocoPhillips
Johanna Fiksdal	Norwegian Delegation to the OECD/IEA
Tim Gould	IEA, Paris
Gary Isaksen	ExxonMobil
Jostein Dahl Karlsen	IEA, GOT
Michael Kerby	ExxonMobil
Vassilios Kougionas	EU-Commission DG RTD
Michael Layer	IEA Got/NR Canada
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Tomoko Uesawa	International Energy Agency
Huanzhi Zhang	CNPC

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References

Chapter 1

International Energy Agency (IEA), 2019. World Energy Outlook 2019 with projections to 2050. International Energy Agency, Paris, France. https://www.iea.org/reports/world-energy-outlook-2019.

Intergovernmental Panel on Climate Change (IPCC), 2018. Global Warming of 1.5°C. IPCC Secretariat World Meteorological Organization, Geneva, Switzerland.

Chapter 2

Joint Global Change Research Institute. Global Change Assessment Model. http://www.globalchange.umd.edu/gcam/ (accessed Feb 24, 2020).

GREET Model. https://greet.es.anl.gov/.

AWARE-USA Model. https://greet.es.anl.gov/publication-aware_us

Paul Scherrer Institute. The MERGE-ETL Model. https://www.psi.ch/sites/default/files/import/eem/ModelsEN/2012MergeDescription.pdf (accessed Feb 24, 2020).

Stanford Environmental Assessment & Optimization Group. OPGEE: The Oil Production Greenhouse Gas Emissions Estimator. https://eao.stanford.edu/research-areas/opgee (accessed Feb 24, 2020).

Joint Global Change Research Institute. The Soil and Water Assessment Tool. https://swat.tamu.edu/ (accessed Feb 24, 2020). Joint Global Change Research Institute. A Community Emissions Data System (CEDS) for Historical Emissions. http://www.globalchange.umd.edu/ceds/ (accessed Feb 24, 2020).

NTNU, EU Horizon 2020 Programme. A The SET-Nav Project (Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation). http://www.set-nav.eu/ (accessed Feb 24, 2020).

NTNU, EU Horizon 2020 Programme. INVADE Horizon 2020. https://h2020invade.eu/ (accessed May 14, 2020).

NTNU, Energy Modeling Hub https://www.ntnu.edu/iot/energy/energy-models-hub (accessed May 14, 2020).

Ecole Polytechnique Institute. Open Input-output (IO) Canada. http://www.ciraig.org/en/open_io_canada/ (accessed Feb 24, 2020). Ecole Polytechnique Institute. Quebec Life Cycle Assessment Inventory database. http://www.ciraig.org/en/bd-icv.php/ (accessed Feb 24, 2020).

Ecole Polytechnique Institute. The Impact World Water Tool. http://www.ciraig.org/en/watertool.php (accessed Feb 24, 2020).

Paul Scherrer Institute. Swiss TIMES Energy system Model. https://www.psi.ch/en/eem/projects/swiss-times-energy-system-model-stem-for-transition-scenario-analyses (accessed Feb 24, 2020). Paul Scherrer Institute. European Swiss TIMES Electricity Model. https://www.psi.ch/en/eem/projects/european-swiss-times-electricity-model (accessed Feb 24, 2020).

Paul Scherrer Institute. Global Multi-regional MARKAL (GMM) Model. https://www.psi.ch/en/eem/methods-and-tools (accessed Feb 24, 2020). Paul Scherrer Institute. BEM (Bi-level electricity modeling). https://www.psi.ch/en/eem/projects/bem-bi-level-electricity-modeling-oligopolistic-capacity-expansion-with-subsequent (accessed Feb 24, 2020).

Netherlands Environmental Assessment Agency. Towards a Global Integrated Sustainability Model (GISMO). https://www.pbl.nl/sites/default/files/downloads/550025002_0.pdf. (accessed Feb 24, 2020).

Netherlands Environmental Assessment Agency. IMAGE: Integrated Model to Assess the Global Environment. https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation. (accessed Feb 24, 2020).

Center for Global Trade Analysis. Global Trade Analysis Project (GTAP). https://www.gtap.agecon.purdue.edu/ (accessed Feb 24, 2020).

US Department of Agriculture. The forest and agricultural sector optimization model (FASOM). https://www.fs.usda.gov/treesearch/pubs/2876 (accessed Feb 24, 2020).

Potsdam Institute for Climate Impact Research. REMIND.https://www.pik-potsdam.de/research/transformation-pathways/models/remind/remind (accessed Feb 24, 2020).

UN Environment. Global LCA Data Network (GLAD). https://www.lifecycleinitiative.org/resources-2/global-lca-data-network-glad/ (accessed Feb 24, 2020).

Sustainable Management Promotion Organization. Multiple Interface Life Cycle Assessment (MiLCA). https://www.milca-milca.net/english/ (accessed Feb 24, 2020).

International Institute for Sustainability Analysis and Strategies. Global Emissions Model for integrated Systems (GEMIS). http://iinas.org/gemis.html (accessed Feb 24, 2020).

Ifu Hamburg. Umberto LCA+. https://www.ifu.com/en/umberto/lca-software/ (accessed Feb 24, 2020). Potsdam Institute for Climate Impact Research. Model of Agricultural Production and its Impact on the Environment (MAgPIE). https://www.pik-potsdam.de/research/projects/activities/land-use-modelling/magpie/magpie-2013-model-of-agricultural-production-and-its-impact-on-the-environment (accessed Feb 24, 2020).

EU Commissions. Integrated Database of the European Energy System (JRC-IDEES). https://ec.europa.eu/jrc/en/publication/jrc-integrated-database-european-energy-system (accessed Feb 24, 2020).

MIT (2018) The Future of Nuclear Energy in a Carbon-Constrained World. http://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/ (accessed Feb 24, 2020).

Chapter 3

Abella JP, Bergerson JA. 2012. “Model to Investigate Energy and Greenhouse Gas Emissions Implications of Refining Petroleum: Impacts of Crude Quality and Refinery Configuration.” *Environ Sci Technol*. 46,13037–47. doi:10.1021/es3018682.

Ciroth A. 2007. ICT for environment in life cycle applications openLCA — A new open source software for life cycle assessment. *Int J Life Cycle Assess*.12, 209–10. doi:10.1065/lca2007.06.337.

Frischknecht R, Heath G, Raugei M, Sinha P, de Wild-Scholten M, Fthenakis V, et al. 2016. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 3rd ed. IEA PVPS Task 12 Int Energy Agency Photovolt Power Syst Progr.

Gençer E, Tawarmalani M, Agrawal R. 2015. Integrated Solar Thermal Hydrogen and Power Coproduction Process for Continuous Power Supply and Production of Chemicals. *Computer Aided Chemical Engineering*. 37, 50076-5. doi:10.1016/B978-0-444-63576-1.

Gençer E, Agrawal R. 2017. Strategy to synthesize integrated solar energy coproduction processes with optimal process intensification. Case study: Efficient solar thermal hydrogen production. *Comput Chem Eng*. 105, 328–47. doi:10.1016/j.compchemeng.2017.01.038.

Herrmann IT, Moltesen A. 2015. Does it matter which Life Cycle Assessment (LCA) tool you choose? – a comparative assessment of SimaPro and GaBi. *J Clean Prod*. 86, 163–9. doi:10.1016/J.JCLEPRO.2014.08.004.

ISO 14040. The International Standards Organisation. Environmental management — Life cycle assessment — Principles and framework. ISO 14040 2006;2006:1–28. doi:10.1136/bmj.332.7550.1107.

ISO. Environmental management - Life cycle assessment - Requirements and guidelines, ISO 14044, International Organization for Standardization 2006;2006:652–68. doi:10.1007/s11367-011-0297-3.

Miller I, Gençer E, O'Sullivan F. 2018. A General Model for Estimating Emissions from Integrated Power Generation and Energy Storage. Case Study: Integration of Solar Photovoltaic Power and Wind Power with Batteries. *Processes*. doi:10.3390/pr6120267.

Miller I, Gençer E, Vogelbaum HS, Brown PR, Torkamani S, O'Sullivan FM. 2019 Parametric modeling of life cycle greenhouse gas emissions from photovoltaic power. *Appl Energy*. 238, 760–74. doi:10.1016/j.apenergy.2019.01.012.

Miller I, Gençer E, O'Sullivan FM. 2019. Modeling Impacts of Tracking on Greenhouse Gas Emissions from Photovoltaic Power. *Comput Aided Chem Eng*. 46,1057–62. doi:10.1016/B978-0-12-818634-3.50177-6.

PRé Sustainability. Manual: SimaPro Tutorial n.d. https://support.simapro.com/articles/Manual/SimaPro-Tutorial/?l=en_US&c=Products%3ASimaPro%3ASP_Tutorials&fs=Search&pn=1 (accessed July 22, 2019).

Singh M, Vyas A, Steiner E. 2004. VISION Model: description of model used to estimate the impact of highway vehicle technologies and fuels on energy use and carbon emissions to 2050. doi:10.2172/822561.

Squared Consultants Inc. GHGenius n.d. https://www.ghgenius.ca/index.php (accessed July 22, 2019).

Stanciulescu V, Fleming J. 2006. Life Cycle Assessment of Transportation Fuels and GHGenius. 2006 IEEE EIC Clim. Chang. Conf., IEEE, p. 1–11. doi:10.1109/EICCCC.2006.277203.

thinkstep. What is GaBi Software n.d. https://www.gabi-software.com/america/overview/what-is-gabi-software/ (accessed July 22, 2019).

U.S. EIA. 2019. Annual Energy Outlook 2019 with projections to 2050. Annu Energy Outlook 2019 with Proj to 2050. 44,1–64. doi:DOE/EIA-0383(2012) U.S.

U.S. EPA. 2018. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017: Updates Under Consideration for Incorporating GHGRP Data.

U.S. EPA. 2018. Air Markets Program Data 2018.

U.S. EPA. 2018. Fuel Economy Data 2018. https://www.fueleconomy.gov/feg/download.shtml.

Wang MQ, Q M. GREET 1.5 - transportation fuel-cycle model - Vol. 1 : methodology, development, use, and results. Argonne, IL (United States): 1999. doi:10.2172/14775.

Federal Highway Administration (FHWA). 2009. National household travel survey. Washington, DC.

Chapter 4

Aguiar, A., Narayanan, B., McDougall, R., 2016. An overview of the GTAP 9 data base. *J. Global Economics*. 1 (1), 181–208.

Bovenberg, A.L., Goulder, L.H., 1996. Optimal environmental taxation in the presence of other taxes: general-equilibrium analyses. *Am. Econ*. Rev. 86 (4), 985–1000.

Chen, Y-H., Paltsev, S., Reilly, J.M., Morris, J.F., Babiker, M., 2016. Long-term economic modeling for climate change assessment. *Econ. Model*. 52, 867–883.

Chen, Y-H., Paltsev, S., Reilly, J.M., Morris, J.F., Babiker, M., 2015. The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. MIT JPSPGC Report 125 (October, 46 p. (https://globalchange.mit.edu/sites/default/files/MITJPSPGC_Rpt278.pdf)).

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., Schieberle, C., Friedrich, R., Janssens-Maenhout, G., 2019. High resolution temporal profiles in the Emissions Database for Global Atmospheric Research (EDGAR), Nature Scientific Data.

Ghandi, A. and Paltsev, S., 2019. Representing a Deployment of Light-Duty Internal Combustion and Electric Vehicles in Economy-Wide Models. MIT Joint Program Technical Note 17. (http://globalchange.mit.edu/publication/17199).

Gunturu, U.B and Schlosser, C.A., 2015. Behavior of the aggeragate wind resource in the ISO regions in the United States. *Applied Energy*. 144, 175–181.

Gurgel, A., Reilly, J., Paltsev, S., 2007. Potential land use implications of a global biofuels industry. *J. Agric. Food Ind. Organ.* 5 (2) Article 9.

International Energy Agency (IEA), 2018. World Energy Outlook. International Energy Agency, Paris, France (iea.org/weo2018/).

Intergovernmental Panel on Climate Change (IPCC), 2014a. Fifth assessment report. IPCC Secretariat World Meteorological Organization, Geneva, Switzerland.

Intergovernmental Panel on Climate Change (IPCC), 2014b. Climate change 2014 synthesis report: summary for policymakers. IPCC Secretariat, World Meteorological Organization, Geneva, Switzerland.

Jacoby, H.D., Chen, Y.-H.H., 2014. Expectations for a new climate agreement. MIT JPSPGC Report 264 August, 24 p. (http://globalchange.mit.edu/files/document/MITJPSPGC_ Rpt264.pdf).

Karplus, V.J., Paltsev, S., Babiker, M., Reilly, J.M., 2013a. Should a vehicle fuel economy standard be combined with an economy-wide greenhouse gas emissions constraint? Implications for energy and climate policy in the United States. *Energy Econ*. 36, 322–333.

Karplus, V.J., Paltsev, S., Babiker, M., Reilly, J.M., 2013b. Applying engineering and fleet de- tail to represent passenger vehicle transport in a computable general equilibrium model. *Econ. Model*. 30, 295–305.

Morris, J., J. Farrell, H. Kheshgi, H. Thomann, H. Chen, S. Paltsev, H. Herzog, 2019, Representing the Costs of Low-Carbon Power Generation in Multi-region Multi-sector Energy-Economic Models, *International Journal of Greenhouse Gas Control*, 87, 170-187.

Nam, K.-M., Waugh, C.J., Paltsev, S., Reilly, J.M., Karplus, V.J., 2013. 2013: carbon co- benefits of tighter SO2 and NOx regulations in China. Glob. Environ. Chang. 23 (6), 1648–1661.

Narayanan, G., Badri, T.W. Hertel, Walmsley, T.L., 2012. GTAP 8 data base documentation — chapter 1: introduction. Center for Global Trade Analysis, Department of Agri- cultural Economics. Purdue University (March (https://www.gtap.agecon.purdue.edu/resources/download/5673.pdf)).

Rubin, S.R., Davison, J.E., Herzog, H.J., 2015. The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*. 40, 378–400.

Rutherford, T.F., Rutstrom, E.E., Tarr, D.G., 1997. Morocco's free trade agreement with the European community. *Econ. Model*. 14 (2), 237–269.

Sokolov, A.P., Stone, P.H., Forest, C.E., Prinn, R.G., Sarofim, M.C., Webster, M., Paltsev, S., Schlosser, C.A., Kicklighter, D., Dutkiewicz, S., Reilly, J., Wang, C., Felzer, B., Melillo, J., Jacoby, H.D., 2009. Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters. *J. Clim*. 22 (19), 5175–5204. http://dx.doi.org/10.1175/2009JCLI2863.1.

Tapia-Ahumada, K., Octaviano, C., Rausch, S., érez-Arriaga, I., 2015. Modeling intermittent renewable electricity technologies in general equilibrium models. *Econ. Model*. 51, 242–262.

van der Mensbrugghe, 2010. The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model. The World Bank (http://siteresources. worldbank.org/INTPROSPECTS/Resources/334934-1314986341738/Env7_1Jan10b. pdf).

Webster, M., Sokolov, A.P., Reilly, J.M., Forest, C.E., Paltsev, S., Schlosser, A., Wang, C., Kicklighter, D., Sarofim, M., Melillo, J., Prinn, R.G., Jacoby, H.D., 2012. Analysis of cli- mate policy targets under uncertainty. *Clim. Chang.* 112 (3–4), 569–583.

Winchester, N., McConnachie, D., Wollersheim, C., Waitz, I.A., 2013. Economic and emissions impacts of renewable fuel goals for aviation in the US. Transp. Res. A Policy Pract. 58, 116–128.

Zhou, J., Latorre, M.C., 2014. How FDI influences the triangular trade pattern among China, East Asia and the U.S.? A CGE analysis of the sector of electronics in China. *Econ. Model*. 44 (Supplement 1), S77–S88.

Chapter 5

Dimanchev, E., S. Paltsev, M. Yuan, D. Rothenberg, C. Tessum, J. Marshall and N. Selin, 2019, "Health Co-Benefits of Sub-National Renewable Energy Policy in the U.S," *Environmental Research Letters*, 14(8), 085012.

Heywood, John, and Don Mackenzie, eds. 2015. On the Road toward 2050: Potential for substantial reductions in light-duty vehicle energy use and greenhouse gas emissions. Cambridge, MA: Massachusetts Institute of Technology. http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/On-the-Road-toward-2050.pdf

Nam, K.-M., N. Selin, J. Reilly, and S. Paltsev, 2010, "Measuring Welfare Loss Caused by Air Pollution in Europe: A CGE Analysis," *Energy Policy*, 38(9), 5059-5071.

National Petroleum Council (NPC). 2012. Advancing Technology for America's Transportation Future. Washington, D.C.: NPC. https://www.npc.org/reports/trans.html

National Research Council (NRC). 2013. Transitions to Alternative Vehicles and Fuels. Washington, D.C.: National Academies Press. https://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels

Nealer, Rachael, David Reichmuth, and Don Anair. 2015. Cleaner Cars from Cradle to Grave. Cambridge, MA: Union of Concerned Scientists. http://www.ucsusa.org/EVlifecycle

Massachusetts Institute of Technology (MIT). 2019. Insights into future mobility. http://energy.mit.edu/wp-content/uploads/2019/11/Insights-into-Future-Mobility.pdf.

Appendix A: Calculating Relative Costs of Power Generating Technologies in the EPPA Model

Appendix A provides the details of the markup (i.e., ration of technology cost to average wholesale electricity price) calculations provided in Tables 4 and 5. For convenience, we provide the same tables here denoted as Tables A1 and A2. To explain in detail how the markups in Tables A1 and A2 are calculated, we use the column labeled "Coal" in Table 4 to illustrate.

Table A1: Markup calculation for the U.S. for established power generation technologies (in 2015$).

		Units	Coal	Gas	Biomass	Wind	Solar	Nuclear
[1]	"Overnight" Capital Cost	$/kW	2148	1031	4181	1845	1581	4286
[2]	SCALED Overnight Capital Cost	$/kW	2365	1135	4602	2031	1740	4718
[3]	**Total Capital Requirement**	**$/kW**	**2743**	**1226**	**5339**	**2194**	**1879**	**6133**
[4]	Capital Recovery Charge Rate	%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
[5]	Fixed O&M	$/kW/year	39	30	109	50	26	71
[6]	Variable O&M	$/kWh	0.0035	0.0028	0.0054	0.0147	0.0168	0.0035
[7]	Project Life	years	20	20	20	20	20	20
[8]	Capacity Factor	%	85%	85%	80%	35%	20%	85%
[9]	(Capacity Factor Wind)							
[10]	(Capacity Factor Biomass/NGCC)							
[11]	Operating Hours	hours/year	7446	7446	7008	3066	1752	7446
[12]	Capital Recovery Required	$/kWh	0.0389	0.0174	0.0805	0.0756	0.1133	0.0870
[13]	Fixed O&M Recovery Required	$/kWh	0.0052	0.0041	0.0155	0.0165	0.0146	0.0095
[14]	Efficiency, HHV	%	42%	53%	30%			33%
[15]	Heat Rate, HHV	MJ/kWh	8.63	6.76	12.00	0	0	11.06
[16]	Fuel Cost	$/GJ	2.08	4.16	3.14	0.00	0.00	0.87
[17]	Fuel Cost per kWh	$/kWh	0.0179	0.0281	0.0377	0.0000	0.0000	0.0096
[18]	**Levelized Cost of Electricity**	**$/kWh**	**0.0656**	**0.0523**	**0.1391**	**0.1068**	**0.1447**	**0.1097**
[19]	Transmission and Distribution	$/kWh	0.03	0.03	0.03	0.03	0.03	0.03
[20]	**Levelized Cost of Electricity incl. T&D**	**$/kWh**	**0.0956**	**0.0823**	**0.1691**	**0.1368**	**0.1747**	**0.1397**
[21]	EPPA Base Year Elec Price	$/kWh	0.0924	0.0924	0.0924	0.0924	0.0924	0.0924
[22]	**Markup Over Base Elec Price**		**1.03**	**0.89**	**1.83**	**1.48**	**1.89**	**1.51**

Row [1]. According to IEA (2015), the overnight capital cost of building a new coal-based power plant is $2148/kW (entered in row [1], Table A1). This IEA number is a globally averaged cost.

Row [2]. The globally averaged overnight capital cost is multiplied by a capital scaling factor to obtain the overnight capital costs for the U.S., which appears in row [2]. Capital scaling factors (or capital scalars) are obtained based on the relative cost of capital in electricity in a particular region to the globally averaged capital cost for the plants represented in IEA (2015) data. The regional cost of capital is from GTAP dataset (Aguiar et al., 2016). For the U.S., the scaling factor is 1.1. A full list of capital scaling factors is reported in Table 6.

Row [3]. The scaled overnight cost is multiplied by a factor of (1 + 0.04*construction time in years) to obtain the total capital requirement appearing in row [3]. Based on the assumed 4-year construction period for a coal power plant, the scaled overnight cost is multiplied by a factor of 1.16.

Row [4]. The cost of capital is taken to be 8.5%. Following EIA (2017), we use a 20-year project economic life for all types of plants (row [7]). This results in a capital recovery charge of 10.6%.

Rows [5-6]. Both the fixed and variable O&M costs for coal are from IEA (2015), with costs of $39/kW/year and $0.0035/kWh, respectively.

Row [7]. The project economic life is taken to be 20 years based on EIA (2017).

Rows [8-11]. The capacity factor [8] for a new coal plant is assumed to be 85% based on IEA (2015), and from this, the total number of operational hours per year [11] is determined.

Row [12]. In order to calculate the capital recovery required [12], the capital recovery charge rate [4] of 10.6% is multiplied by the total capital requirement [3]. This yields the total capital required per kilowatt per year, and by dividing by the total operating hours per year [11], the capital recovery in $/kWh [12] is obtained.

Row [13]. The fixed O&M recovery [13] is calculated by dividing the fixed O&M costs per year [5] by the total number of operational hours per year [11].

Rows [14-15]. The heat rate [15] is obtained from efficiency numbers [14] from IEA (2015), which is given on a low heating value (LHV) basis. We convert this to a high heating value (HHV) basis and report all efficiencies and heat rates in the Tables 4 and 5 on a HHV basis. They are 42% and 8.63 MJ/kWh for coal.

Rows [16-17]. The fuel costs [16] are from the GTAP database, and it is $2.02/GJ for coal. By multiplying the heat rate [15] and the fuel cost [16] (and dividing by 1000), the fuel cost per kWh [17] is found.

Rows [18-20]. The sum of the variable O&M [6], the capital recovery required [12], the fixed O&M required [13], and the fuel cost per kWh [17] yields the levelized cost of electricity [18] for technologies without CCS. For coal, the LCOE is $0.066/kWh. For a model like EPPA, total costs including transmission and distribution are required. Adding $0.03/kWh for transmission and distribution [19] for traditional technologies yields the levelized cost with transmission and distribution costs included [20]. That is $0.096/kWh for coal.

Rows [21-22]. Based on this information, the markup [22] is calculated for a particular region by dividing the levelized cost of electricity including transmission and distribution [20] by electricity price in that region [21] from GTAP. The markup then reflects the relative costs of all technologies in the base year of the EPPA model, which is the information the model needs to optimize electricity investment decisions. The markup for Coal is 1.03.

In addition to Coal, Table A1 also shows these calculations for Gas, Biomass, Wind, Solar and Nuclear, and Table A2 shows them for Coal with CCS, Gas with CCS, BECCS, Coal+Bio CCS, Gas with Advanced CCS, WindGas and WindBio.

Rows [23-29]. Plants with CCS have to account for the cost of transportation and storage of CO_2. The calculation is shown in lines [23] through [29] of Table 5. The amount of fossil fuel consumption comes from the heat rate [15]. That number is then multiplied by the carbon content [24] of the various fuel types, in kilograms of carbon per gigajoule (kgC/GJ), to give kgC per kWh [24]. The carbon content of each fossil fuel was retrieved from the U.S. Environmental Protection Agency (EPA, 1998). Then, the carbon output per kWh of the technology [24] is converted to kg of CO2 per kWh [25] by multiplying by the ratio of their molecular weights (44/12). An assumption of $10/tCO2 for transportation and storage costs [28] is based on Rubin et al (2015). CO2 transportation and storage cost is then multiplied by the amount of CO2 emissions captured [27] to determine the cost of transportation and storage in $/kWh [29]. This value [29] is included in the levelized cost [18] for CCS technologies.

Table A2. Markup calculation for the U.S. for advanced power generation technologies (in 2015$)

		Units	Coal with CCS	Gas with CCS	BECCS	Coal+Bio CCS	Gas with Advanced CCS	WindGas	WindBio
[1]	"Overnight" Capital Cost	$/kW	4100		8867			2536	6026
[2]	SCALED Overnight Capital Cost	$/kW	4514		9762			2792	6634
[3]	**Total Capital Requirem ent**	**$/kW**	**5417**	**2336**	**11714**	**5630**	**1431**	**3015**	**7165**
[4]	Capital Recovery Charge Rate	%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
[5]	Fixed O&M	$/kW/year	62	59	169	78	35	58	159
[6]	Variable O&M	$/kWh	0.0057	0.0065	0.0087	0.0057	0.0028	0.0141	0.0132
[7]	Project Life	years	20	20	20	20	20	20	20
[8]	Capacity Factor	%	85%	85%	80%	85%	85%	42%	42%
[9]	(Capacity Factor Wind)							35%	35%
[10]	(Capacity Factor Biomass/NGCC)							7%	7%
[11]	Operating Hours	hours/year	7446	7446	7008	7446	7446	3679.2	3679.2
[12]	Capital Recovery Required	$/kWh	0.0769	0.0332	0.1766	0.0799	0.0203	0.0866	0.2058
[13]	Fixed O&M Recovery Required	$/kWh	0.0084	0.0079	0.0242	0.0104	0.0048	0.0157	0.0433
[14]	Efficiency, HHV	%	33%	45%	21%	32%	53%	40%	30%
[15]	Heat Rate, HHV	MJ/kWh	10.92	8.02	17.35	11.14	6.77	9.02	12.00
[16]	Fuel Cost	$/GJ	2.08	4.16	3.14	2.08	4.16	4.16	3.14
[17]	Fuel Cost per kWh	$/kWh	0.0227	0.0333	0.0544	0.0243	0.0281	0.0031	0.0033
[18]	**Levelized Cost of Electricity**	**$/kWh**	**0.1230**	**0.0845**	**0.2783**	**0.1298**	**0.0594**	**0.1194**	**0.2655**
[19]	Transmission and Distribution	$/kWh	0.03	0.03	0.03	0.03	0.03	0.04	0.04
[20]	**Levelized Cost of Electricity incl. T&D**	**$/kWh**	**0.15**	**0.11**	**0.31**	**0.16**	**0.09**	**0.16**	**0.31**
[21]	EPPA Base Year Elec Price	$/kWh	0.09	0.09	0.09	0.09	0.09	0.09	0.09
[22]	**Markup Over Base Elec Price**		**1.66**	**1.24**	**3.34**	**1.73**	**0.97**	**1.73**	**3.31**
	For CCS								
[23]	Carbon Content	kgC/GJ	24.686	13.700	24.975	24.686	13.700		
[24]	Carbon Emissions	kgC/kWh	0.2696	0.1098	0.4333	0.2750	0.0928		
[25]	Carbon Dioxide Emissions	kgCO2/kWh	0.9886	0.4027	1.5887	1.0082	0.3401		
[26]	Percent Emissions Captured	%	95%	90%	90%	95%	100%		
[27]	CO2 Emissions Captured	kgCO2/kWh	0.9392	0.3624	1.4298	0.9578	0.3401		
[28]	Cost of CO2 T&S	$/tCO2	10	10	10	10	10		
[29]	CO2 Transportation and Storage Cost	$/KWh	0.0094	0.0036	0.0143	0.0096	0.0034		