MIT Climate Grand Challenge: Tough to Decarbonize Transportation

Appendix E: Assessment

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Table of Contents

E.1. Introduction

This project has a single goal: to sustainably reduce the climate forcing due to tough-to-decarbonize transportation modes to zero by 2050. However, this begs the question of what is “sustainable”.

Bringing climate impacts to zero is inherently equitable, because there remains no disbenefit to be inequitably distributed. It is also plausible to set goals of “net zero”. Since the overall climate impact is mostly independent of the source, offsetting a positive climate forcing (e.g., from biofuel soot emissions) with a negative emission (e.g., direct capture and geological sequestration of atmospheric CO_2) can be treated as equivalent to zero emissions at both locations.

However, decarbonization is also likely to lead to changes in other parts of the economy and environment. For example, decarbonization may lead to changes in what raw materials are used within the economy, prices of products, and other forms of environmental degradation. It is impractical to set a goal that these other forms of impact which are relevant to this project are also brought to zero. In absolute terms, the additional power generation, raw material acquisition, infrastructure development, and manufacturing required to produce (for example) any hydrogen-based economy will result in some areas being subject to greater water stress and air pollution than would otherwise have been the case, even if the total exposure to both harms is reduced. Similarly, some segments of the population will suffer greater economic harm or loss of access to transportation than others if travel or freight become more expensive.

In principle, we could calculate what economists refer to as the “compensating variation” for each person. The compensating variation measures the amount of money the individual needs to return them to the same level of welfare they enjoyed prior to the change. Therefore, we could calculate a series of transfers required to make everyone whole with respect to these other impacts. However, such a large set of transfers would be politically infeasible.

Accordingly, in this work we set two requirements to be accomplished by 2050, and one goal to be optimized:

1. The solution must not involve the movement of any additional carbon from the geological to the atmospheric reservoir. This means zero use of fossil fuels.
2. Net climate impacts (measured as global mean radiative forcing) due to tough-to-decarbonize transportation must be reduced permanently to zero by 2050. This may

include some negative emissions to counteract (e.g.) climate forcing due to land use change or condensation trails.

3. The future technological and policy trajectory which achieves these goals must do so while maximizing progress towards the 17 United Nations Sustainable Development Goals (SDGs), relative to our reference trajectories (Appendix D). This means evaluating both the degree to which impacts are reduced globally and the degree to which changes are (in)equitably distributed. However, due to the unique contribution of transportation to air pollution, we stipulate that our solution must also reduce global net air pollution from T2DT by 95% by 2050, relative to 2019 (i.e. pre-pandemic).

Whereas our requirements can be directly evaluated using geophysical models alone (Section E.2), our optimization goal requires a more holistic approach which incorporates economic modeling and accounts for inequity of outcomes. The quantitative evaluation from geophysical and economic models, as discussed briefly in Section 4.1 of the T2DT white paper and in detail throughout this technical appendix, will provide the base information required for this analysis. A key outcome of the T2DT project will be the development of an analytical framework which can estimate the effect that a “sustainable T2DT pathway” has on global equity.

This will require a dedicated research task (see Section E.3), undertaken through collaborative research between MIT researchers in policy, environmental impact assessment, and economics, with substantial stakeholder involvement. Initial avenues of research will center on the “inclusive wealth” paradigm. Our expectation is that, within three years, we will progress from pure quantification of physical and economic impacts to an SDG-focused quantitative assessment approach. This will enable each proposed T2DT solution to be evaluated quantitatively against the SDGs, including weighing different changes in outcome equity such as the relative effect of redistributing air pollution and water stress.

Following these sections, we provide a hypothetical example of how they might be applied to a sample solution (Section E.4), followed by a brief listing of initiatives at MIT who would likely be involved in the assessment component of this project (Section E.5) and a summary of immediate research priorities for this component (Section E.6).

E.2. Quantitative assessment tools and methods

Close coordination of the tools (models and procedures) to be used in the assessments of the environmental & economic impacts of decarbonizing the tough-to-decarbonize modes (aviation, shipping and heavy-duty trucking) will be needed. This section describes each of the tools already in use at MIT which will be harnessed in service of our goals, and which will provide the quantitative data necessary to inform our larger evaluation framework.

Figure E 1 shows conceptually how several existing tools at MIT will be connected to quantify the environmental and economic impacts of decarbonizing the T2DT modes. Before impact evaluation can take place, we first need to estimate how the proposed solutions will change human activity. This will be performed through three components. The Sustainable Energy System and Analysis Modeling Environment (SESAME; see Section E.2.2) will be applied to estimate total emissions of lifecycle greenhouse gases (GHGs), while the Economic Projection and Policy Analysis model (EPPA; see Section E.2.1) will be used to estimate the total demand for each T2DT mode as part of its role in economic projection (see below). The results from SESAME and EPPA will be provided to the Global Spatial and Temporal Emissions Modeling tool (GSTEM; see Section E.2.3), which will be used to generate a spatially and temporally resolved estimate of lifecycle pollutants from each mode.

EPPA is part of the MIT Integrated Global System Model Framework (IGSM) (Monier et al., 2018; Prinn, 2013). Designed to analyze interactions between humans and the Earth system, this comprehensive set of linked models is used to study the causes, consequences and potential solutions to problems that arise from global change. The IGSM framework consists primarily of two interacting components— EPPA, as discussed above, and the MIT Earth System model (MESM; see Section E.2.4). MESM will estimate global changes in land and water, consistent with the results from EPPA, SESAME, and GSTEM. Air pollution and human health impacts will be estimated using the GEOS-Chem High Performance chemistry transport model (GCHP; see Section E.2.5). Collectively, these tools will enable the team to quantify metrics ranging from health damages due to air quality degradation through to potential crop failure due to water stress. This set of tools is not exhaustive, but would provide the basis for future research and development.

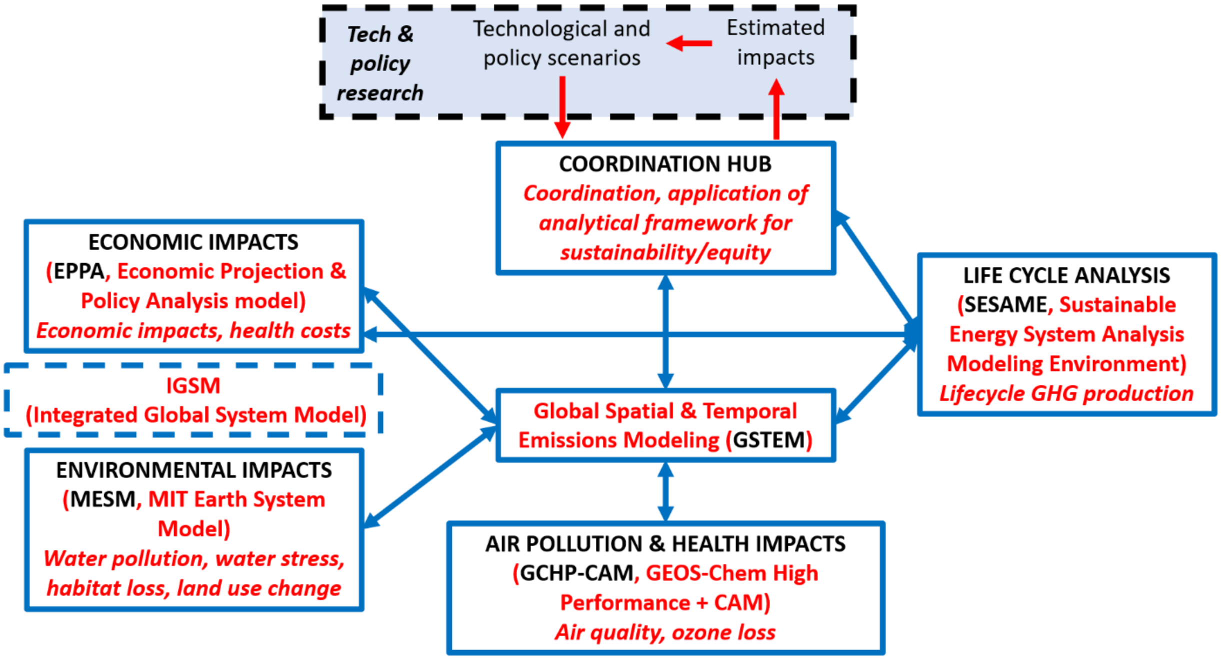

Figure E 1. Schematic of interactions between quantitative components. Quantitative impact estimates are integrated through the coordination hub and fed back to the technological and policy researchers, providing a feedback mechanism.

E.2.1. Quantifying global economic consequences: EPPA

The Economic Projection and Policy Analysis (EPPA) model provides projections of world economic development at a regional and sectoral level, including deployment of specific energy and transportation technologies, the economic implications of greenhouse gas (GHG) emissions, conventional air pollution, land-use change, food demand, and natural resource use (Chen et al., 2016). The default level of resolution is 18 world regions (including USA, Europe, China, India, Brazil, Africa, The Middle East and others). For specific projects, resolution can be changed based on the underlying economic dataset that includes 141 countries/aggregate regions.

EPPA can explore different regional policy settings (emission constraints, carbon pricing, fuel and technology subsidies, fuel technology standards, etc.) and simulate the evolution of economic, demographic, trade and technological processes involved in activities that affect the environment. The model can be run up to 2100 in 5-year intervals (a timeframe to 2050 might be more suitable for particular needs). In the main EPPA version, transportation is represented by private transportation and industrial transportation. In a special version, industrial transportation is further divided into land, water, and air transport. The model can project economic impacts (e.g., change in GDP, sectoral output, fuel prices, fuel use) and emission impacts (GHG and air pollutants by sector and by region). For biofuels, the model tracks land use and its competition with other land uses (for food, livestock, forestry, etc.). EPPA can provide projections of international trade flows (at a level of the EPPA sectoral resolution) and the associated transportation needs under different policy and technology scenarios.

EPPA needs information on relative costs of production of alternative fuels and transportation technologies and their likely evolution. Information on the cost components (capital requirement, labor requirement, operation and maintenance, etc) is desirable. Assumptions about the likely policies are needed for scenario analysis.

E.2.2. Estimating global lifecycle emissions of greenhouse gases: SESAME

One challenge in determining how best to achieve net-zero emissions is providing a rigorous and consistent framework for calculation of life cycle emissions of greenhouse gases for each of the production pathways for producing the potential fuels for powering transportation. In the case of hydrogen, this includes emissions in each of the conversion and transmission steps, whether the life cycle starts with natural gas extraction or electricity production. Likewise, the emissions from production of powertrains and infrastructure must be accounted for. The MIT Energy Initiative (MITEI) has developed a modeling tool for performing end-to-end Life Cycle Analysis for fuels and electricity and many other contributors to global emissions. Sustainable Energy System Analysis Modelling Environment (SESAME) is MITEI's system-scale energy analysis tool to assess the system-level greenhouse gas (GHG) emissions.

A foundation to SESAME is process flowsheet simulations for the conversion processes that make up each of the pathways. One of the workhorses for these calculations is Aspen Plus, a widely-used commercial software tool which was originally developed at MIT and then spun-out into a startup company 40 years ago. MIT has free access to use this software for teaching and for research and Aspen Plus has been used by MITEI and other MIT researchers to model production of biofuels, hydrogen, and ammonia.

SESAME is an ongoing development effort. The current version can model more than 1000 pathways, representing about 80% of U.S. greenhouse gas emissions. These pathways include many options for electricity and hydrogen production, as well as conventional pathways for production of gasoline and diesel. More detail can be found in Gençer et al. (2020).

E.2.3. Estimating the global magnitude and distribution of pollutant emissions: GSTEM

Even once a techno-political pathway has been identified, the emissions of greenhouse gases, air pollutants, and potentially other environmental hazards must be quantified before the impacts can be known. Whereas global totals are sufficient for greenhouse gases, the impacts of pollutants such as nitrogen oxides (NO_x) depend on the spatial and temporal distribution of their emission. This document deals only with direct emissions, and not indirect emissions (e.g., from vehicle production or from electricity generation for battery charging).

GSTEM will bring together several existing capabilities at MIT, while integrating state-of-the-art tools and methods from the literature where they are needed. For greenhouse gases, emissions can be estimated based on simple global scaling approaches. Activity projects from the EPPA model (see "Economic-Energy-Emissions-Policy Modeling") can be used to estimate the total fuel use by each tough-to-decarbonize sector, from which total CO_2 emissions can be estimated on a stoichiometric basis.

For all other species, sector-specific modeling tools are needed. For aviation, we will use the Aircraft Emissions Inventory Code (AEIC) (Simone et al., 2013). AEIC can simulate the flight trajectories of every civil airliner over the course of a single year based on flight schedule data, aircraft performance data, and standardized engine emissions data. A prior project has demonstrated the use of AEIC in a forward-looking capacity, estimating global aviation emissions for 2035 with and without supersonic aviation (Speth et al., 2021).

For maritime shipping, the methods developed by Zhang et al. (2021) provide a baseline for an AEIC-like tool, while for heavy-duty trucking a tool will need to be developed from scratch. However, in each case modern-day inventories are available which can provide a basis for development.

For each of the three modes, the emissions model will require schedule information, vehicle performance data, and engine emissions data. Building on the example of AEIC, this will allow the model to produce a global, spatially- and temporally-resolved inventory of emissions.

E.2.4. Quantifying impacts on land and water: MESM

To explore climate-related impacts of human-forced change to the land systems, we continue to build upon a Global Land System (GLS) (Schlosser et al., 2007) within the MIT Earth-System Model, or MESM (Sokolov et al., 2018). MESM allows for a comprehensive risk-based approach to regional climate changes (Adam Schlosser et al., 2013). In addition, we study the availability and potability of water supplies via a linked Water Resource System (WRS) that explicitly tracks water-resource management and quality (Boehlert et al., 2015). In its current implementation, the MESM-GLS-WRS model system assesses projections from models of economic activity, population, energy consumption, land management, land use/cultivation, as well as weather and climate. All these can then be used to explore and quantify the evolving risks across the natural and managed terrestrial systems. To date, we have used this model system to explore a wide range of land-climate impacts, feedbacks, and risks relating to:

biomass/biofuels (Hallgren et al., 2013; Reilly et al., 2012); climate-related ecosystem responses (Gao et al., 2013; Kicklighter et al., 2019; Saikawa et al., 2013; Sokolov et al., 2008); regional hydroclimatic risk (Schlosser et al., 2021); climate-related impacts and risks to conventional and renewable energy systems (Baker et al., 2014; Fant, Adam Schlosser, et al., 2016; Gao, Adam Schlosser, and Morgan, 2018); and evolving water resource risks across developed and developing nations of the world (Arndt et al., 2019; Blanc et al., 2014; Fant, Schlosser, et al., 2016; Gao, Adam Schlosser, Fant, et al., 2018; Schlosser et al., 2014).

Any transformation (at scale) of energy systems to low carbon technologies will require considerable penetration of biomass-based fuels into energy supplies. The decisions made as to the: location, deployment, management, feedstock, irrigation, and waste of/from the biomass production will have complex and compounding effects to downstream water systems. In addition, any aggressive low-carbon policy will result in avoided risks from extreme events and subsequent damages to the land systems. The resulting water flow impacts infrastructure, including the river transportation system of ports and levees as well as energy infrastructure and buildings, agriculture, economic activity, populations, and ecosystems. Water quality affects populations, ecosystems, economic activity, and the energy sector. We can capture these interactions in our models and explore them under a wide range of scenarios, including scenarios of different economic and infrastructure development and population trajectories for the region. We can investigate how the frequency of droughts and floods may change over time, and identify potential tipping points (for example, areas that are not currently at flood risk, but may become so in the future). We can explore how development upstream may have impacts downstream. We can also explore decision-making around flood risk, including how decisions might differ if based on local impacts vs. impacts on the system as a whole. Independent local decisions could lead to an unstable system, while considering the whole system could make the system more stable.

The inputs required by the GLS module are gridded hourly timeseries of: precipitation, incident shortwave radiation, incoming longwave radiation, surface-air temperature, windspeed, specific humidity. In addition, the GLS model system requires information on global landcover type – that can also be time evolving (but not required). The minimal inputs required by WRS are: population; GDP; thermoelectric production (and cooling technology); daily precipitation; daily minimum/maximum/average temperature; irrigated area and technology; crop type and coverage; and fertilizer loading.

E.2.5. Quantifying air pollution and ozone layer damage: GCHP-CAM

One of the known environmental impacts of transportation is air quality degradation from atmospheric emissions. This includes direct effects (e.g., tailpipe emissions) and indirect effects (e.g., emissions from manufacturing, from electricity production to charge electric vehicles, and biogenic emissions from biomass feedstocks used to create biofuel). GCHP-CAM can be applied to quantify these air quality impacts in terms of changes in near-surface pollutants such as fine particulate matter ($PM_{2.5}$), ozone, and NO_2.

Our GCHP system allows us to estimate the change in atmospheric composition and air quality resulting from a change in emissions at scales down to 25 km globally. The core component of this is GEOS-Chem in its high-performance configuration (GCHP). Through GCHP, we can estimate how surface concentrations of criteria pollutants including ozone, fine particulate matter, and NO_x are likely to respond to a change in the magnitude or distribution of emissions related with any of the three tough-to-decarbonize sectors. This includes quantifying how remote changes (e.g., aviation emissions) will affect both global quantities such as ozone layer thickness, and local quantities such as urban air quality. More detail can be found at www.geos-chem.org or in model description papers (Bey et al., 2001; Bindle et al., 2021; Eastham et al., 2014, 2018; Long et al., 2015; Park, 2004).

GCHP-CAM needs only the projected changes in the global distribution of air pollutant emissions and precursors (e.g., NO_x, SO_x, ammonia). The model needs data to be provided as a gridded set of emission rates (e.g., hourly mean emission rate of NO_x in each 0.5°×0.5° grid cell, latitude by longitude). By default, GCHP-CAM can either be run with historical meteorological data, or it can simulate the air quality response under three different future climate scenarios (ranging from 3.7 W/m^2 to 10 W/m^2 radiative forcing in 2100).

E.2.6. Quantifying human health impacts of air pollution

One of the non-carbon impacts of transportation is the effect that attributable pollution has on public health. This research group has a long record of estimating the public health consequences of different interventions at a local, regional, and global scale, and will bring those capabilities to bear when evaluating the consequences of different decarbonization scenarios.

Mortality due to multiple causes (e.g., respiratory disease) can be estimated for current-day conditions, pending the production of surface pollution maps from the GCHP-CAM framework. These estimates include the effects of exposure to fine particulate matter ($PM_{2.5}$) and ozone based on concentration response functions derived from epidemiological research

(Burnett et al., 2018; Turner et al., 2015; Vodonos et al., 2018). In each case, a Monte Carlo sampling approach is employed to quantify uncertainty in impacts resulting from uncertainty in the concentration response function. For each scenario, the change in mortality rate due to air pollution can be estimated for each country worldwide. Impacts can be monetized using the value of statistical life (VSL), which is based on the willingness to pay to avoid a marginal increase in the risk of death (US EPA, 2014). Our analysis will calculate the financial impacts under a variety of VSL assumptions.

E.3. An analytical framework for sustainability and equity

When developing the framework for equity, the assigned researcher will look into performing a social lifecycle analysis (Social LCA). The researcher should determine the scope of the LCA (i.e. cradle-to-gate vs. cradle-to-grave), equity measurements to be considered (i.e. qualitative vs. quantitative), and impact categories. The UN Environmental Programme's recommendations for Social LCA categories include the worker, consumer, local community, society, and value chain's role in the product development/use. Potential social issues to consider include transportation worker rights in lithium or other natural resource extraction supply chains, equality between developing and non-developing countries for technology development, and air pollution affecting disadvantaged communities.

E.4. Example assessment: hydrogen as a fuel

An example of the application of the Assessment Tools is the examination of the use of hydrogen as a fuel for the shipping-H_2, trucking-H_2 and short-range aviation-H_2 systems. To meet our decarbonizing goals, this hydrogen may be produced for example from electrolysis of water using zero-carbon electric power (so-called "green" H_2). In the scenario below, we assume that a plausible hydrogen infrastructure, distribution, and emissions scenario has been provided by the technical and policy area researchers, coordinated through the T2DT leadership.

As background, hydrogen is currently present in the atmosphere at mole fractions of around 520 ppb in the Southern Hemisphere and 560 ppb in the Northern Hemisphere (https://agage.mit.edu/data/agage-data). It is primarily produced in situ from photolysis of air-pollution-derived HCHO and secondarily emitted from biomass burning and internal combustion engines; it is consumed primarily by soil microbes and secondarily by reaction with atmospheric OH (Xiao et al., 2007). Its estimated total source is 103 +/- 10 Tg/yr - a reasonable benchmark for assessing new hydrogen emissions - and its estimated atmospheric lifetime (total atmospheric amount/total atmospheric loss rate) is 1.8 +/- 0.3 years (Xiao et al., 2007).

Life cycle analysis (SESAME) will provide all hydrogen (leakage), GHG and pollutant emissions during H2 production and consumption. Economic analysis (EPPA) will model supply and demand for each sector and resultant supply, demand, and price per unit mass of hydrogen. The economic assessment will also consider the impact on national and regional economies of manufacture and use of vehicles, production and consumption of hydrogen, and costs of human health and environmental impacts into account. The GSTEM will provide regional disaggregation of national and global total emissions where needed.

As far as environmental impacts are concerned, hydrogen has been recognized as an "indirect" greenhouse gas due to its reaction with the hydroxyl (OH) radical. This means adding more H_2 to the atmosphere would reduce OH (the primary sink for methane and all other hydrogen-containing greenhouse gases, and for CO, NO_x, SO_2, and many organic gases) and thereby increase the lifetimes and thus atmospheric abundances and radiative forcing of these gases. **The primary climate impact of hydrogen can be expressed in terms of the total increases in non-CO_2 GHGs induced by the H_2-induced lowering of OH expressed as CO_2-equivalents (ppm) or radiative forcing (W/m^2)**.

To evaluate these climate (and associated air pollution) impacts, we will use the GCHP-CAM and MESM models. The needed inputs from GSTEM are regionally and temporally resolved emissions to the atmosphere of H_2, NO_x and GHGs emitted during H_2 production and consumption. The in situ atmospheric sinks of H_2 (mostly reaction with tropospheric OH), are present in these models (or easily added). However, the major sink for H_2 is uptake by soils as noted above.

The current estimated atmospheric lifetime of H_2 due to soil uptake (total atmospheric amount/total soil loss rate) is 2.3 years (Xiao et al., 2007). While the simplest assumption for modeling is to presume that this lifetime is constant, that would be unexpected given that the soil sink for H_2 is a complex function of soil microbial speciation, metabolism, life cycles, nutrients, climate, and environment (Meredith et al., 2014, 2017). Our initial assessments will assume lifetime constancy; that is total soil loss rate = (total atmospheric amount)/ (lifetime of H_2 due to soil uptake). In other words, the soil loss rate rises linearly with atmospheric H_2 abundance. **However, further research is essential for setting a more science-based threshold for the global hydrogen leakage rate.** That will require 1 post-doc for the first 3 years of this project.

GCHP-CAM, MESM, APCEMM, and the other environmental impact assessment tools available to our team will be deployed to quantify the fossil fuel consumption and net climate forcing (both total and resulting from T2DT) for the scenario. This will provide an assessment of how close we have come to achieving our climate goals. Outputs from the same tools will allow us to estimate surface conditions, water availability, stratospheric ozone, and other physical quantities, from which impact metrics such as mortality due to air pollution can be derived. These impact metrics will be integrated with economic metrics from (e.g.) EPPA through the research defined in Section E.3 to yield a holistic assessment of the global effects of the scenario.

E.5. Relevant initiatives at MIT

The following Labs and Centers at MIT all have deep experience with regards to quantitative evaluation of the economic and environmental consequences of different technological and policy pathways. This project draws upon and will benefit from their expertise:

- MIT Joint Program on the Science and Policy of Global Change
- MIT Center for Global Change Science
- MIT Center for Energy and Environmental Policy Research
- MIT Energy Initiative
- MIT Mobility Initiative
- MIT Laboratory for Aviation and the Environment
- MIT Climate and Sustainability Consortium

E.6. Immediate research priorities

In addition to the task of building a quantitative, analytical framework for evaluation of our progress towards sustainable and equitable T2DT, some early priorities for development have been identified which could improve the ability of our quantitative tools (Section E.2) to represent the economic and environmental impacts of a given solution. This list is not complete, and includes tasks which may or may not be necessary depending on the priorities identified by the upstream technology and policy researchers. However, it demonstrates some of the potentially fruitful research directions which may be undertaken as part of this project.

The major task not represented here is the iterative process of performing large ensemble simulations of each given solution pathway and returning the impact estimates to the broader team. Although a significant undertaking, this task is considered conceptually straightforward, and as such the priorities below focus on new capabilities which may need to be developed as part of this project.

E.6.1. Inter-model coupling

Although most of the models described in Section E.2 have been used in a “coupled” framework before (e.g. EPPA and MESM working together in the IGSM), the full constellation of models has never before been brought together in service of a single research goal. As a result, some quantities are predicted independently and/or inconsistently between components. Harmonizing the models to ensure a consistent understanding of (e.g.) land use change will require an initial research task, followed by ongoing research effort throughout the program’s duration.

E.6.2. Extending EPPA

A representation of transportation technologies in EPPA can be expanded to introduce an explicit modeling of hydrogen-based and electric heavy-duty land transportation, ammonia/hydrogen-based shipping, biofuel-based jet fuel. Pricing of the associated air pollution emissions (NO_x, N_2O, NH_3) can be introduced for the policy scenario analysis (pricing of CO_2 is already included). A detailed look at major world regions to capture region-specific technology development and their economic implications can be provided. Energy and economic impacts at sectoral and regional levels can be explored, land use change information (in hectares for different use) can be modeled and evaluated, and consistent emission profiles (with other socioeconomic information) can be provided to other project participants for air pollution and climate modeling. Depending on the scope, the level of effort includes one full-time post-doctoral associate/research scientist as well as supervision support for the duration of the project.

E.6.3. Extending SESAME

Although SESAME already includes most features and pathways required to support full life-cycle (LCA) and techno-economic analyses (TEA) for the T2DT project, some additional development will be needed. This falls into two categories: incremental enhancements (e.g. LCA for conversion) and pathway analyses. The latter category includes collecting the performance parameters for the conversion technologies and powertrains, as well as the infrastructure requirements. This work must be completed for each of the potential pathways. The pathways analysis must also cover the breakthrough technologies that will be developed by the MIT team during the execution of this 5-year project.

E.6.4. Building GSTEM

For all three transportation modes, new tools will be needed which can translate the technical and policy trajectories developed by the T2DT research team into global, spatially-and temporally-resolved emissions inventories. Development of these inventories will be inherently multidisciplinary and collaborative, as every technical and political choice will affect the nature and distribution of the emissions. We will also need to ensure that all relevant models have a common and consistent representation of emissions, which will necessitate an initial model harmonization phase. The total necessary research time is anticipated to be equivalent to two PhDs (i.e. approximately five years each for two graduate students).

E.6.5. Extending MESM

MESM is already well positioned to estimate water stress and water quality but has not been explicitly designed to capture changes which might occur due to very large scale biofuel production. In order to better represent potential changes in water quality, MESM would benefit from the implementation of a more detailed, process-based representation of irrigation, fertilization, and herbicide and pesticide application to the agriculture sector of its land system model. This could be further extended by the development and implementation of a model of aquaculture farms for biofuels, depending on the needs identified by the technological and policy teams. See Section E.4 for adding hydrogen sources and sinks to MESM.

E.6.6. Extending GCHP-CAM

Due to GEOS-Chem's nature as a “community” model, there are already multiple research groups working on improving its representation of atmospheric chemistry, such that specific improvements for this project can be more narrowly defined. One such improvement is with regards to the treatment of hydrogen, which GEOS-Chem currently prescribes. A small research effort (~1 postdoc year) could likely determine the atmospheric chemical response to an increase in near-surface or at-altitude hydrogen emissions. A larger research effort (>1 postdoc year) would be needed to incorporate a subgrid model of urban chemistry, which might improve GEOS-Chem's representation of the effects of ground transportation, coastal shipping, and in-port emissions. See Section E.4 for adding hydrogen sources and sinks to GCHP-CAM.

E.6.7. Extending health impact estimation

Our tools currently focus on estimation of mortality but could be expanded to cover morbidity outcomes such as asthma, lost work days, and even dementia (Ru et al., 2021). Other health impact mechanisms could also be incorporated, including changes in skin cancer incidence due to ozone loss, mortality due to increased heat stress, and effect of exposure to NO_2. Each such expansion would likely require around three months of research from a single senior graduate student or a postdoctoral fellow.

A larger extension would be to implement projections of population density, demographics, and mortality rates. Our current approach relies on current-day estimates, but changes in the distribution and health of future populations may cause shifts in the areas most impacted by a specific technological or policy change. This would also enable the group to use population and demographic projections which are consistent with the assumptions made by the policy team. This extension would likely require a year of research from a single senior graduate student or a postdoctoral fellow.

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