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CALIFORNIA

Wildfire smoke may carry 'mind-bending' amounts of fungi and bacteria, scientists say

Cars drive along the Golden Gate Bridge under an orange, smoke-filled sky in the middle of the day as massive wildfires burned in Northern California on Sept. 12. Scientists are concerned that wildfire smoke contains microbes that can cause illness. (Harold Postic / AFP/ Getty Images)

By JOSEPH SERNA

FEB. 1, 2021 6 AM PT

When wildfires roar through a forest and bulldozers dig into the earth to stop advancing flames, they may be churning more into the air than just clouds of dust and smoke, scientists say.

Those dark, billowing plumes of smoke that rise on waves of heat during the day and sink into valleys as the night air cools may be transporting countless living microbes that can seep into our lungs or cling to our skin and clothing, according to research published recently in Science. In some cases, researchers fear that airborne pathogens could sicken firefighters or downwind residents.

“We were inspired to write this because we recognize that there are many trillions of microbes in smoke that haven’t really been incorporated in an understanding … of human health,” said Leda Kobziar, a University of Idaho associate professor in wildland fire science. “At this point, it’s really unknown. The diversity of microbes that we’ve found are really mind-bending.”

As this recent fire seasons suggests, the need to understand what’s in the wildfire smoke we can’t help but breathe and how it may affect us has never been more pronounced, but scientists say we are seriously behind the curve.

Wildfires burned across more than 10.2 million acres of the United States in 2020, federal statistics show, including some 4.2 million acres in California, where a greater number of residents were exposed to smoke for a longer period of time than ever before.

Wildfire smoke now accounts for up to half of all fine-particle pollution in the Western U.S., according to researchers. Although there are many studies on the long-term impacts to human health from urban air pollution and short-term impacts from wildfire smoke, there's little known about the multitude of ways the latter can hurt us over a lifetime.

"Frankly, we don't really know about the long-term effects of wildfire smoke because community exposures haven't been long-term before," said Dr. John Balmes, a professor of medicine at UC San Francisco and a member of the California Air Resources Board.

But humans — and Californians in particular — should expect to inhale more wildfire smoke in the future.

Scientists say the planet will continue warming for decades to come, even if humans suddenly collectively act to stop climate change. This warming, and other factors, are contributing to ever more destructive wildfires. The state's forests, meanwhile, are struggling to adapt and native plants are being displaced by faster-burning invasive species.

Add to those trends a global pandemic that attacks the respiratory system, and microbe-filled fire smoke every year could be considered a growing health risk, researchers say. They wonder whether microbes in wildfire smoke could make cancer patients more vulnerable to infections or make children with asthma more prone to developing pneumonia.

Scientists believe some microbes survive and even proliferate in wildfire, where heat scorches the ground and leaves behind a layer of carbon that shields microbes within the earth from intense heat. Others survive in the air because wildfire particulates can absorb the sun's otherwise lethal ultraviolet radiation, the scientists said. And still other spores are likely spread on wind currents caused by fire.

Kobziar and study co-author George Thompson III, an associate professor of medicine at UC Davis, said that up until now, the connection between microbes and wildfires has been anecdotal — such as the tendency for wildland firefighters to get sick with Valley fever after working on an incident. The illness is contracted by inhaling spores of the fungi genus *Coccidioides*.

"We have more questions than answers at this point," Thompson said. "Our lungs are exposed to pathogens every day we don't think much of. But [what] if we increase the number of microbes in there with fire?"

In 2018, for example, the Kern County Fire Department sought a $100,000 grant to get assistance in cutting fuel breaks — which disturb the soil — because their firefighters would get sick after doing the work. Data show that Valley fever cases spike on the county's valley floor every fall, just as fire season is underway in the surrounding hills.

"Aerosolized, microbes, spores, or fungal conidia … have the potential to travel hundreds of miles, depending on fire behavior and atmospheric conditions, and are eventually deposited or inhaled downwind of a fire," Kobziar and Thompson wrote in their paper.

Yet, determining what pathogens exist in wildfire smoke has been difficult.

The National Oceanic and Atmospheric Administration, NASA and team of chemists, physicists, biologists and forest and fire ecologists from a number of universities have been collaborating for years to study wildfire smoke around the country, under the assumption that nobody will be immune to its effects in the future.

"As the climate changes, as the temperature warms up, as we build houses in places that are surrounded by human populations and housing development expand into regions susceptible to fires, it's a matter of time," said Berry Lefero, manager of NASA's Tropospheric Composition Program, which includes a DC-8 jetliner that circles the globe studying wildfire smoke, ozone and aerosols in the atmosphere's lower layer.

Through the combined work of these researchers, scientists hope, the public and healthcare workers will one day be able to receive timely, accurate forecasts on where wildfire smoke will go, what specific health hazards it poses, and what people in its path should do to prepare beyond the boilerplate advice to stay indoors.

To solve the riddle of what microbes are in the smoke and why, Kobziar and Thompson need to understand what type of fuel is burning, like a grass, shrub, or tree; how much of it there was initially; how severely it was burned (was it just scorched black or completely reduced to ash or something in between?); and where the smoke originated.

Once those variables are determined, there’s the complicated task of actually capturing the smoke, which is by no means uniform, Kobziar said.

In September, Kobziar used a drone to capture samples of the air over Idaho when it was inundated with smoke from fires in Eastern Washington and Oregon. She then placed the samples in a petri dish, added some food that microbes like to eat and waited to see what would happen.

“Even a couple hundred miles away from the source of the smoke, it was still significant,” Kobziar said. “We’re still trying to isolate all the things we found.”

Tim Edwards, president of the firefighters union Local 2881, which represents thousands in the California Department of Forestry and Fire Protection, hopes the scientists’ work can boost his own efforts to get wildland firefighters respirators, since they typically just rely on face masks or bandanas — unlike their urban firefighting counterparts.

It’s not only the dust kicked up in a fire that gets crews sick, Edwards said.

“Now, in a wildland conflagration, you have 1,000 homes burning,” he said. “You burn the house, you don’t know what chemicals they have in that house, all that is on fire and that’s going in your lungs.”

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Joseph Serna is the deputy editor of culture and talent at the Los Angeles Times and helps oversee its career training and recruitment efforts.

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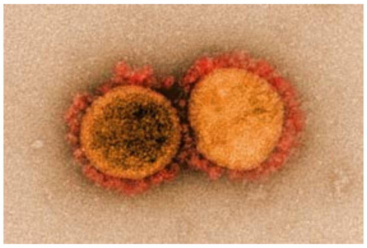

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Late Edition

Today, partly sunny, very cold, windy, high 23. **Tonight,** clear skies, breezy, very cold, low 15. **Tomorrow,** sunny, cold but not so windy, high 28. Weather map appears on Page B6.

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DOUG MILLS/THE NEW YORK TIMES

President Biden and Vice President Kamala Harris at a signing event on Thursday to expand health coverage and restore mandates.

Biden Moves To Fix Cracks In Health Act

Easing Medicaid and Abortion Restrictions

By SHERYL GAY STOLBERG and ABBY GOODNOUGH

WASHINGTON — President Biden on Thursday ordered the Affordable Care Act's health insurance marketplaces reopened to give people throttled by the pandemic economy a new chance to obtain coverage, and he took steps to restore coverage mandates that had been undermined by his predecessor, including protecting those with pre-existing medical conditions.

Thursday's orders also took aim at Trump-era restrictions on Medicaid, especially on work requirements imposed by some states on poor people trying to obtain coverage. Separately, Mr. Biden moved toward overturning his predecessor's restrictions on the use of taxpayer dollars for clinics that counsel patients on abortion, both in the United States and overseas.

Mr. Biden used Thursday's appearance at the White House to begin shoring up health care programs and policies that have been critical to a Democratic resurgence. Perhaps no policy is as important to him as the Affordable Care Act, which he helped secure as President Barack Obama's vice president. President Donald J. Trump tried and failed to overturn the law, then weakened it with executive actions and rules, including making it easier for people to buy cheap, short-term plans that are not required to cover preexisting medical conditions.

"The best way to describe them: to undo the damage Trump has done," Mr. Biden said of his actions during a brief signing ceremony in the Oval Office. "There's nothing new that we're doing here, other than restoring the Affordable Care Act and restoring the Medicaid to the way it was."

Under the order Mr. Biden signed Thursday, a new "special enrollment period" will open on Feb. 15 and run through May 15. A senior administration official said the reopening would be accompanied by the kind of patient outreach — paid advertising, direct outreach to consumers and partnerships with community organizations and advocacy groups — that was abandoned by the Trump administration.

Typically, Americans in the 36 states that rely on the federal marketplace can buy insurance only during a six-week period in the fall, a restriction meant to encourage people to hold coverage even

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G.M. PHASING OUT CARS AND TRUCKS USING GAS BY 2035

PRESSURE ON ITS RIVALS

Automaker's Move Could Have a Huge Impact on Oil Companies

By NEAL E. BOUDETTE and CORAL DAVENPORT

The days of the internal combustion engine are numbered.

General Motors said Thursday that it would phase out petroleum-powered cars and trucks and sell only vehicles that have zero tailpipe emissions by 2035, a seismic shift by one of the world's largest automakers that makes billions of dollars today from gas-guzzling pickup trucks and sport utility vehicles.

The announcement is likely to put pressure on automakers around the world to make similar commitments. It could also embolden President Biden and other elected officials to push for even more aggressive policies to fight climate change. Leaders could point to G.M.'s decision as evidence that even big businesses have decided that it is time for the world to begin to transition away from fossil fuels that have powered the global economy for more than a century.

G.M.'s move is sure to roil the auto industry, which, between car and parts makers, employed about one million people in the United States in 2019, more than any other manufacturing sector by far. It will also have huge ramifications for the oil and gas sector, whose fortunes are closely tied to the internal combustion engine.

A rapid shift by the auto industry could lead to job losses and business failures in related areas. Electric cars don't have transmissions or need oil changes, meaning conventional service stations will have to retool what they do. Electric vehicles also require fewer workers to make, putting traditional manufacturing jobs at risk. At the same time, the move to electric cars will spark a boom in areas like battery manufacturing, mining and charging stations.

Electric cars today are the fastest-growing segment of the auto industry, but they still make up a small proportion of new car sales: about 3 percent of the global total, according to the International Energy Agency. Sales of such cars jumped last year in Europe and China, but they remain niche products in the United States. They are bought primarily by affluent early adopters who are drawn to the luxury models made by Tesla, which dominates the business, and by environmentally conscious consumers.

A spokesman for Ford Motor declined to directly comment on G.M.'s move but said his company was "committed to leading the electric vehicle revolution in the areas where we are strong." Several other automakers, most of them European, have previously pledged more modest steps in the direction that G.M. says it is headed. Daimler, which makes Mercedes-Benz cars, has said it would have an electric or hybrid version of each of its models by 2022, and Volkswagen has prom-

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A New Vaccine Shows Success, With a Caveat

This article is by ***Katie Thomas, Carl Zimmer*** *and* ***Sharon LaFraniere.***

Novavax, a little-known company supported by the U.S. federal government's Operation Warp Speed, said for the first time on Thursday that its Covid-19 vaccine offered robust protection against the virus. But it also found that the vaccine is not as effective against the fast-spreading variant first discovered in South Africa, another setback in the global race to end a pandemic that has already killed more than 2.1 million people.

That could be a problem for the United States, which hours earlier reported its first known cases of the contagious variant in two unrelated people in South Carolina. And it came just days after Moderna and Pfizer said that their vaccines were also less effective against the same variant.

Novavax, which makes one of six vaccine candidates supported by Operation Warp Speed, has been running trials in Britain,

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Republicans' Links to Extremists Draw Scrutiny

Some House Members Have Ties to Groups Involved in Riot

By LUKE BROADWATER and MATTHEW ROSENBERG

WASHINGTON — The video's title was posed as a question, but it left little doubt about where the men who filmed it stood. They called it "The Coming Civil War?" and in its opening seconds, Jim Arroyo, who leads an Arizona chapter of Oath Keepers, a right-wing militia, declared that the conflict had already begun.

To back up his claim, Mr. Arroyo cited Representative Paul Gosar of Arizona, one of the most far-right members of Congress. Mr. Gosar had paid a visit to the local Oath Keepers chapter a few years earlier, Mr. Arroyo recounted, and when asked if the United States was headed for a civil war, the congressman's "response to the group was just flat out: 'We're in it. We just haven't started shooting at each other yet.'"

Less than two months after the video was posted, members of the Oath Keepers were among those with links to extremist groups from around the country who took part in the Jan. 6 attack on the Capitol, prompting new scrutiny of the links between members of Congress and an array of organizations and movements that espouse far-right beliefs.

Nearly 150 House Republicans supported President Donald J. Trump's baseless claims that the election had been stolen from him. But Mr. Gosar and a handful of other Republican members of the House had deeper ties to extremist groups who pushed violent ideas and conspiracy theories and whose members were prominent among those who stormed the halls of Congress in an effort to

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TRUMP THAW The top House Republican tried to mend fences with the ex-president. PAGE A14

JIM HUYLEBROEK FOR THE NEW YORK TIMES

Fearsome Footwear

The white hightop sneakers beloved by the Taliban terrify others. Afghanistan Dispatch. Page A11.

CICELY TYSON, 1924-2021

A Regal Actress Who Radiated Black Strength Across Decades

By ROBERT D. McFADDEN

Cicely Tyson, the stage, screen and television actress whose vivid portrayals of strong African-American women shattered racial stereotypes in the dramatic arts of the 1970s, propelling her to stardom and fame as an exemplar for civil rights, died on Thursday. She was 96.

Her death was announced by her longtime manager, Larry Thompson, who provided no other details.

In a remarkable career of seven decades, Ms. Tyson broke ground for serious Black actors by refusing to take parts that demeaned Black people. She urged Black colleagues to do the same, and often went without work. She was critical of films and television programs that cast Black characters as criminal, servile or immoral, and insisted that African-Americans, even if poor or downtrodden, should be portrayed with dignity.

Her chiseled face and willowy frame, striking even in her 90s, became familiar to millions in more

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BEN SKLAR FOR THE NEW YORK TIMES

Cicely Tyson in 2013 became the oldest person to win a Tony.

New York State Undercounted Nursing Home Deaths, Report Says

Blow to Cuomo's Image on Virus Response

By JESSE McKINLEY and LUIS FERRÉ-SADURNÍ

ALBANY, N.Y. — For most of the past year, Gov. Andrew M. Cuomo has tried to brush away a persistent criticism that undermined his national image as the man who led New York through the pandemic: that his policies had allowed thousands of nursing home residents to die of the virus.

But Mr. Cuomo was dealt a blow when the New York State attorney general, Letitia James, reported on Thursday morning that Mr. Cuomo's administration had undercounted coronavirus-related deaths of state nursing home residents by the thousands.

Just hours later, Ms. James was proved correct, as Health Department officials made public new data that added more than 3,800 deaths to their tally, representing nursing home residents who had died in hospitals and had not previously been counted by the state as nursing home deaths.

The state's acknowledgment increased the overall death toll related to those facilities by more than 40 percent. Ms. James's report had suggested that the state's previous tally could be off by as much as 50 percent.

The findings do not change the overall number of Covid-19 deaths in New York — more than 42,000,

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YaleNews

Surge in digital activity has hidden environmental costs

By Mike Cummings | JANUARY 27, 2021

(© stock.adobe.com)

During the COVID-19 pandemic people across the world have adopted increasingly digital lifestyles. They stream movies, attend Zoom meetings, and sweat through online exercise classes. Many of them, however, are unlikely to consider the environmental impact of this behavior.

A new Yale-led study accounts for the hidden environmental footprint of this surge in digital activity, estimating its carbon emissions, water consumption, and land usage.

Published in the journal Resources, Conservation, and Recycling (https://www.sciencedirect.com/science/article/abs/pii/S0921344920307072) , the study estimates that internet usage increased by up to 40% worldwide following the issuance of stay-at-home orders from January through March 2020 as the virus spread. According to the study, this spike in online activity triggered a demand for up to 42.6 million megawatt-hours of additional electricity to support data transmission and to power data centers — the buildings that house the hardware and data of computer networks, cloud services, and digital applications.

If the world is to transition to a green economy, the authors assert, then these often-overlooked environmental costs must be fully exposed and addressed.

> “Perhaps you don’t need to stream every movie in HD. Perhaps consider switching off the video function during a Zoom meeting when possible.
>
> —KAVEH MADANI

“The pandemic-related switch to digital has important environmental benefits, such as the reduction of travel-related carbon emissions, but the transition to a more digitally-centered world is not as clean as one might think,” said Kaveh Madani (https://cmes.macmillan.yale.edu/people/kaveh-madani) , the Henry Hart Rice Senior Fellow at the Council on Middle East Studies at Yale’s MacMillan Center for International and Area Studies, who led the study. “We want to provide people with the information they need to make good choices, so they don’t develop habits that harm the environment and are difficult to break.”

The other collaborators are from Purdue University and MIT.

If remote working and other physical distancing requirements were to continue through 2021, an additional 34.3 million tons in emissions of carbon dioxide and other greenhouse gases would be generated worldwide, the study forecasts. To offset that would require a forest twice the size of Portugal, the study says. The amount of water consumed would fill 317,200 Olympic-size swimming pools. (Water is used in the generation of electricity and to cool servers and other hardware.) And the land footprint, which includes the area needed to produce the required energy for data processing and transmission, would be the equivalent of the city of Los Angeles.

These rough estimates are based on data reported by individual countries and specific service providers. For example, Netflix reported a 16% spike in daily traffic between January and March 2020. Zoom, the nearly ubiquitous digital meeting platform, reported a tripling of daily usage after initial pandemic-related shutdowns in the United States.

The study recognizes that the changes in internet use do not cause linear changes in energy use and environmental footprints. Yet, the researchers say they hope that their estimates — based on limited available data at the global scale — will encourage researchers, internet users, regulators, and service providers to more carefully examine the overlooked environmental impacts of the internet sector.

Madani and his coauthors urge service providers, including firms that provide cloud-based storage services, and application-based companies — such as YouTube, Zoom, Instagram, Facebook, Twitter, Microsoft, Amazon, TikTok, and Netflix — to continue taking steps to improve efficiency and reduce their energy. But they also call on them to work toward limiting the environmental impact of their products and to share information about their environmental footprints with users.

In addition, they urge policymakers to require digital companies to be transparent about the environmental footprints of their products and enact measures to curb their environmental impact.

There is also role for consumers, who can collectively reduce the internet's environmental footprint and promote sustainability by adopting responsible online behaviors, the researchers said. For example, whenever possible, consumers can lower the quality of streaming video quality from high definition to standard. If 70 million streaming subscribers lowered the quality of their video, it could reduce monthly greenhouse gas emissions by up to 3.5 million tons — the equivalent of eliminating 6% of monthly coal consumption in the United States, according to the study.

"It's about developing responsible behaviors, like switching off the lights in an empty room," Madani said. "That's the spirit of our message. Digital products are constantly improving in quality, but we have power over how we use them. Perhaps you don't need to stream every movie in HD. Perhaps consider switching off the video function during a Zoom meeting when possible. Each of these behaviors can have a big impact collectively."

ENVIRONMENT

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ScienceDaily®
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Scientists take strides towards entirely renewable energy

Date: November 8, 2019

Source: Trinity College Dublin

Summary: Researchers have made a major discovery that will make it immeasurably easier for people (or super-computers) to search for an elusive 'green bullet' catalyst that could ultimately provide entirely renewable energy.

FULL STORY

Scientists from Trinity College Dublin have taken a giant stride towards solving a riddle that would provide the world with entirely renewable, clean energy from which water would be the only waste product.

Reducing humanity's carbon dioxide (CO_2) emissions is arguably the greatest challenge facing 21st century civilisation -- especially given the ever-increasing global population and the heightened energy demands that come with it.

One beacon of hope is the idea that we could use renewable electricity to split water (H_2O) to produce energy-rich hydrogen (H_2), which could then be stored and used in fuel cells. This is an especially interesting prospect in a situation where wind and solar energy sources produce electricity to split water, as this would allow us to store energy for use when those renewable sources are not available.

The essential problem, however, is that water is very stable and requires a great deal of energy to break up. A particularly major hurdle to clear is the energy or "overpotential" associated with the production of oxygen, which is the bottleneck reaction in splitting water to produce H_2.

Although certain elements are effective at splitting water, such as Ruthenium or Iridium (two of the so-called noble metals of the periodic table), these are prohibitively expensive for commercialisation. Other, cheaper options tend to suffer in terms of their efficiency and/or their robustness. In fact, at present, nobody has discovered catalysts that are cost-effective, highly active and robust for significant periods of time.

So, how do you solve such a riddle? Stop before you imagine lab coats, glasses, beakers and funny smells; this work was done entirely through a computer.

By bringing together chemists and theoretical physicists, the Trinity team behind the latest breakthrough combined chemistry smarts with very powerful computers to find one of the "holy grails" of catalysis.

The team, led by Professor Max García-Melchor, made a crucial discovery when investigating molecules which produce oxygen: Science had been underestimating the activity of some of the more reactive catalysts and, as a result, the dreaded "overpotential" hurdle now seems easier to clear. Furthermore, in refining a long-accepted theoretical model used to predict the efficiency of water splitting catalysts, they have made it immeasurably easier for people (or super-computers) to search for the elusive "green bullet" catalyst.

Lead author, Michael Craig, Trinity, is excited to put this insight to use. He said: "We know what we need to optimise now, so it is just a case of finding the right combinations."

The team aims to now use artificial intelligence to put a large number of earth-abundant metals and ligands (which glue them together to generate the catalysts) in a melting pot before assessing which of the near-infinite combinations yield the greatest promise.

In combination, what once looked like an empty canvas now looks more like a paint-by-numbers as the team has established fundamental principles for the design of ideal catalysts.

Professor Max García-Melchor added: "Given the increasingly pressing need to find green energy solutions it is no surprise that scientists have, for some time, been hunting for a magical catalyst that would allow us to split water electrochemically in a cost-effective, reliable way. However, it is no exaggeration to say that before now such a hunt was akin to looking for a needle in a haystack. We are not over the finishing line yet, but we have significantly reduced the size of the haystack and we are convinced that artificial intelligence will help us hoover up plenty of the remaining hay."

He also stressed that: "This research is hugely exciting for a number of reasons and it would be incredible to play a role in making the world a more sustainable place. Additionally, this shows what can happen when researchers from different disciplines come together to apply their expertise to try to solve a problem that affects each and every one of us."

Story Source:

Materials provided by **Trinity College Dublin**. *Note: Content may be edited for style and length.*

Journal Reference:

1. Michael John Craig, Gabriel Coulter, Eoin Dolan, Joaquín Soriano-López, Eric Mates-Torres, Wolfgang Schmitt, Max García-Melchor. **Universal scaling relations for the rational design of molecular water oxidation catalysts with near-zero overpotential**. *Nature Communications*, 2019; 10 (1) DOI: 10.1038/s41467-019-12994-w

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An MIT Energy Initiative Working Paper

July 2020[2]

Maryam Arbabzadeh

Emre Gençer

Jennifer F. Morris

Sergey Paltsev

Robert C. Armstrong

[1] This preread working paper was prepared for the Energy Choice Workshop hosted by the International Energy Association Gas & Oil Technology Collaboration Program "IEA GOT CP" on October 30, 2019.

[2] Originally released as a white paper in October 2019.

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MIT Energy Initiative

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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).

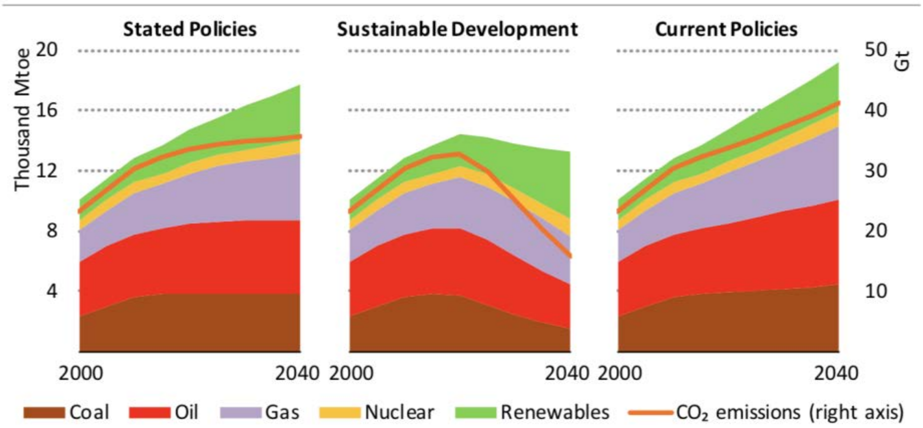

Figure 1 Global primary energy demand by fuel and related CO_2 emissions across stated policies, sustainable development, and current policies scenarios (IEA, 2019).

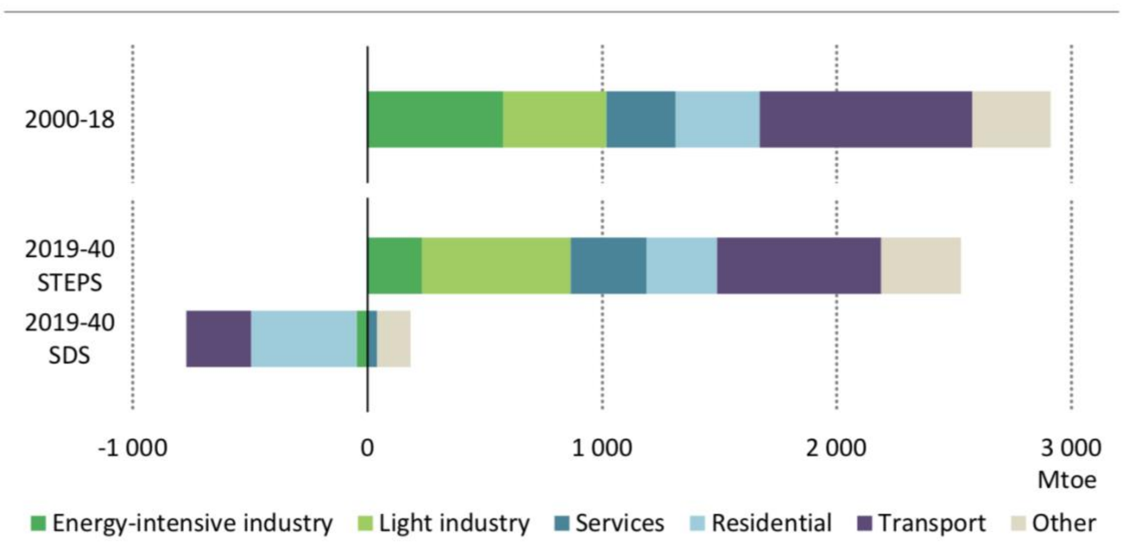

Figure 2 Change by final energy consumption across sectors and scenarios (IEA, 2019).

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.

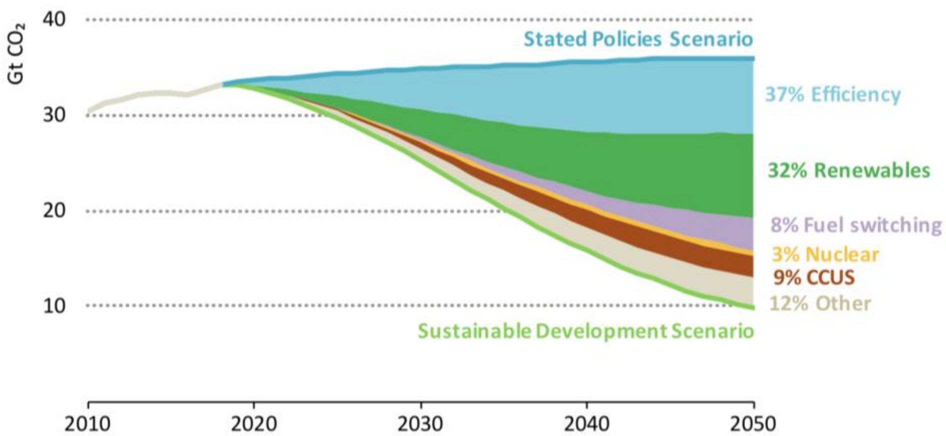

Figure 3 Energy-related CO_2 emissions and reductions by source in the Sustainable Development Scenario compared with the Stated Policies Scenario (IEA, 2019).

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 (Gençer, 2020).

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>
</table>

		○ 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.
GREET Model (The Greenhouse gasses, Regulated Emissions, and Energy use in Transportation Model)	Argonne National Lab	• Publicly available
• An analytical tool that simulates the energy use and emissions output of various vehicle and fuel combination.		
AWARE-US	Argonne National Lab	• Publicly available
• Results of AWARE-US quantify the water stress and the impacts of increase in water consumption in various regions within the U.S.		
The SET-Nav Project (Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation)	NTNU, E.U. Horizon 2020 programme	• Ongoing project
• 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.		
The INVADE Project	NTNU, E.U. Horizon 2020 programme	• Ongoing project
• A flexibility management system using batteries that supports the distribution grid and electricity market while coping with grid limitations.		
Global Gas Model (GGM)	NTNU	• Open access
• 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.		
EMPIRE (European Model for Power System Investment with Renewable Energy)	NTNU	• Open access
• A comprehensive power system model including generation, storage, and transmission capacity expansion.		

• 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>

• 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.		
REMIND	Potsdam Institute for Climate Impact Research	• 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.
• 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.		
Global LCA Data Network (GLAD)	UN Environment	• Publicly available • Web based platform
• 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.		
Multiple Interface Life Cycle Assessment (MiLCA)	Sustainable Management Promotion Organization	• Available to purchase
• A lifecycle assessment (LCA) support system including 3000 process datasets.		
Global Emissions Model for integrated Systems (GEMIS)	International Institute for Sustainability Analysis and Strategy (IINAS)	• A public domain
• A public domain lifecycle and material flow analysis model and database that IINAS provides freely.		
Umberto LCA+	ifu Hamburg	• Available to purchase
• LCA software solutions for product sustainability		
Model of Agricultural Production and its Impact on the Environment (MAgPIE)	Potsdam Institute for Climate Impact Research	• Code available on GitHub
• 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.		
Integrated Database of the European Energy System (JRC-IDEES)	E.U. Commission	• Publicly available
• 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.		

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).

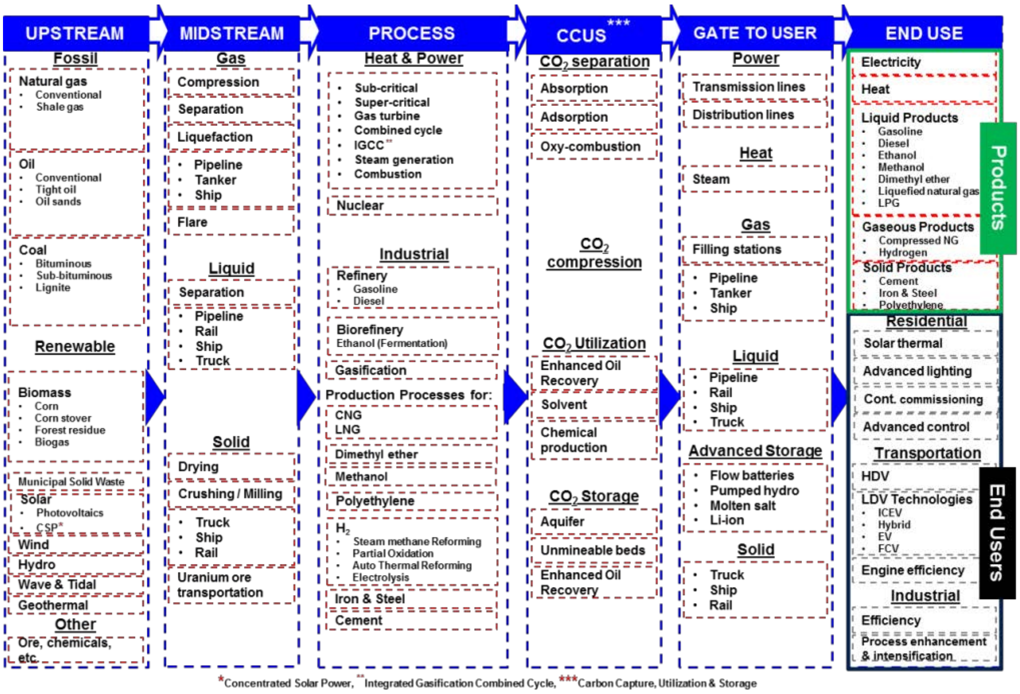

Figure 4 Modular representation of the energy system as defined in SESAME.

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.

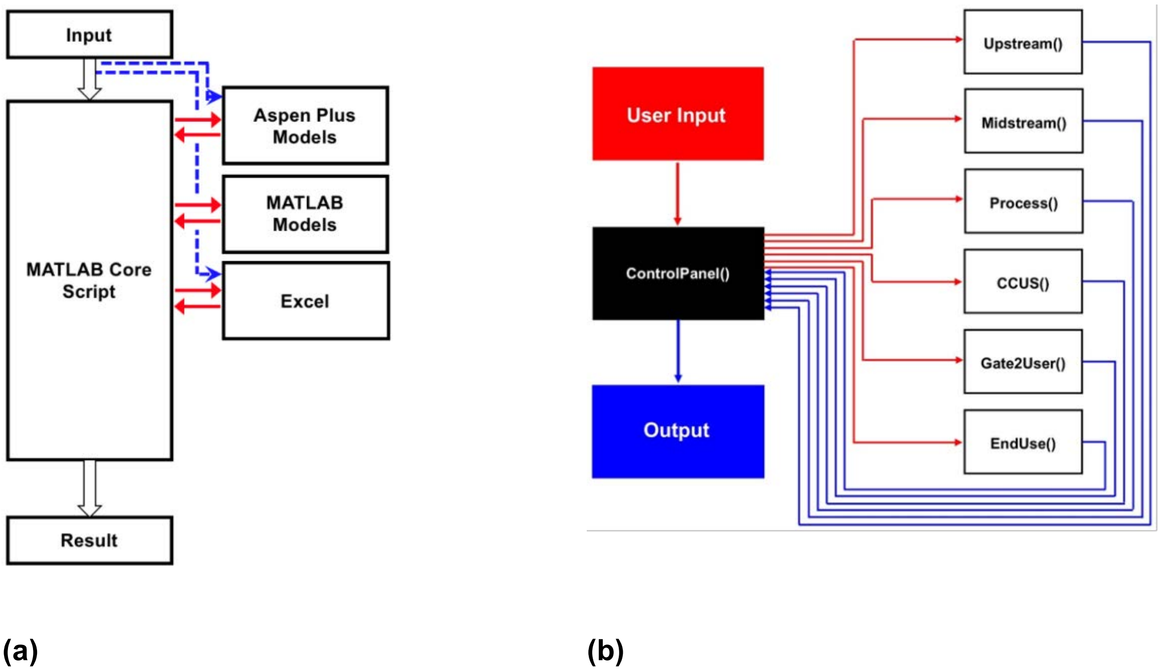

Figure 5 (a) The communication between the MATLAB Core Script and auxiliary components: MATLAB Models, Aspen Plus Models, and Excel models and databases are shown. **(b)** MATLAB is used to develop life step modules, each one of which has its unique structure. Each module is composed of numerous custom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

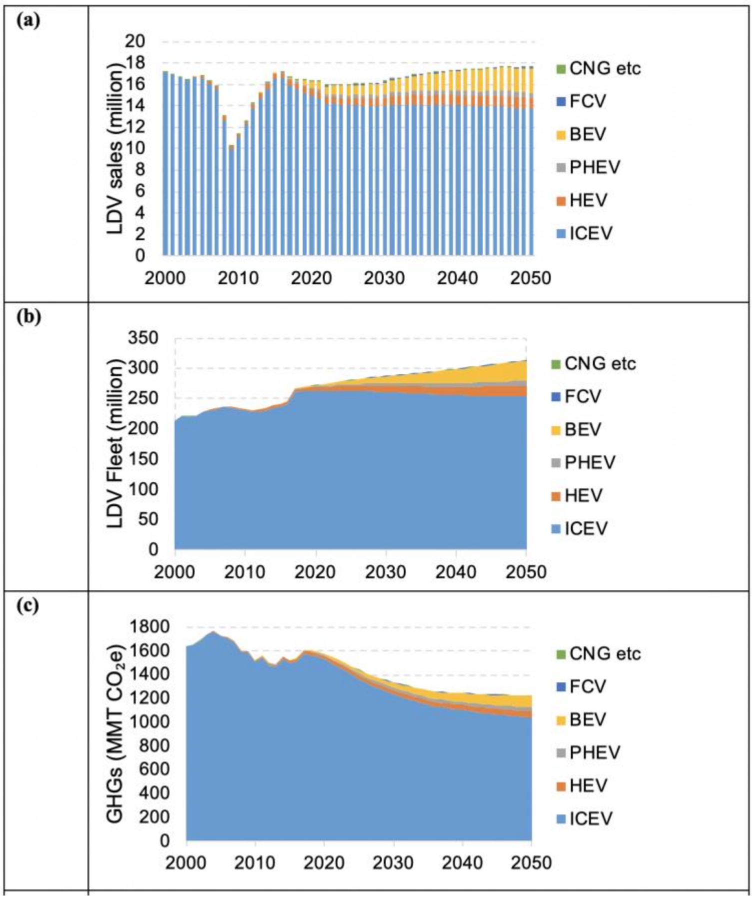

Figure 6 SESAME's vehicle fleet results for the EIA Outlook 2019 baseline case. (a) Passenger vehicle Sales (million), (b) Total LDV fleet (million), (c) GHG emissions (MMtons CO_{2e}) by car type.

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

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.

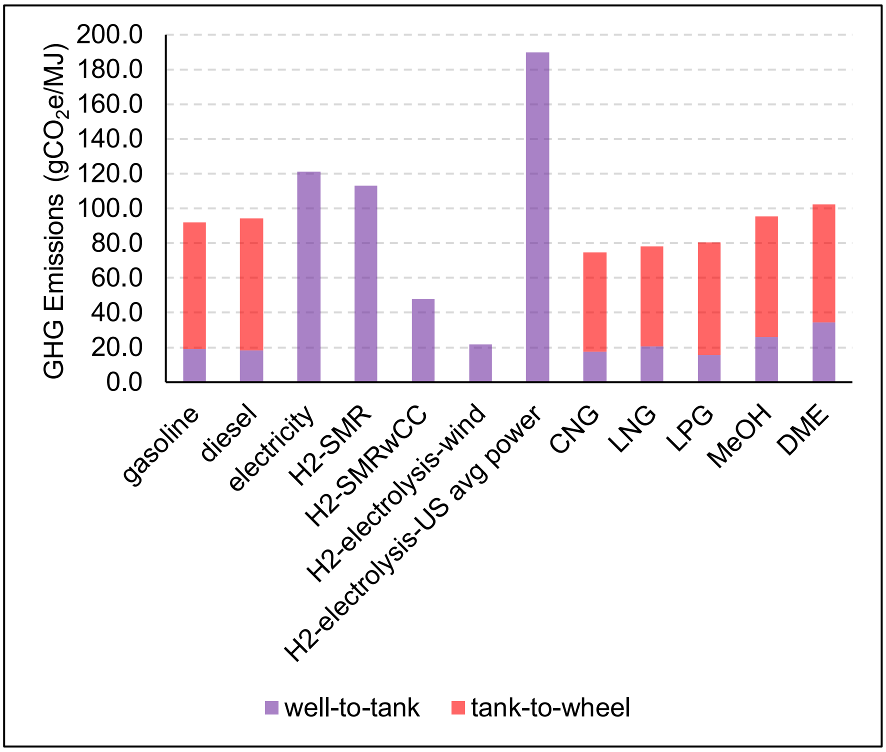

Figure 8 Fuel Cycle GHG Emissions. Electricity and H_2-electrolysis represent U.S. average power cases, assuming the 2018 U.S. grid mix with emission intensity of 437 gCO_2e/kWh. (Note: depending on the input assumptions, the LCA results will change.)

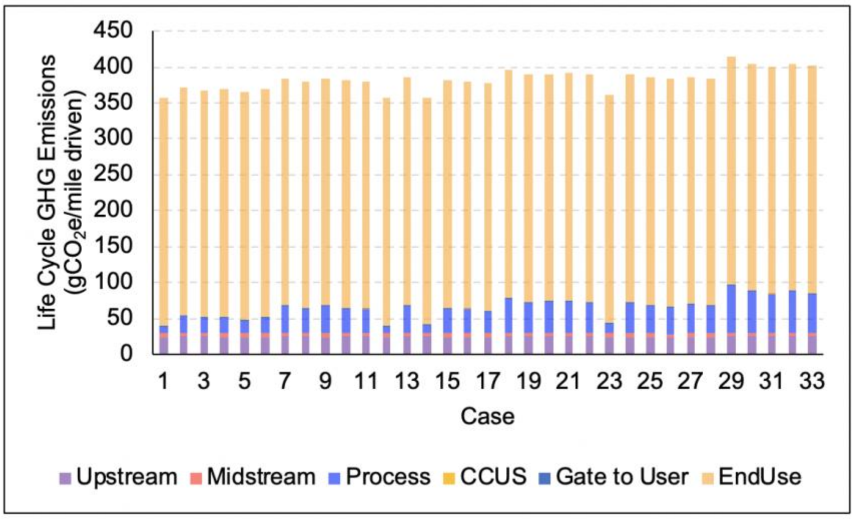

Figure 9 Well-to-wheel LCA GHG emissions (gCO_2e/mile driven) of various crude oil and refinery options included in SESAME for an average diesel light duty vehicle (fuel economy: 26.2 MPG).

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.

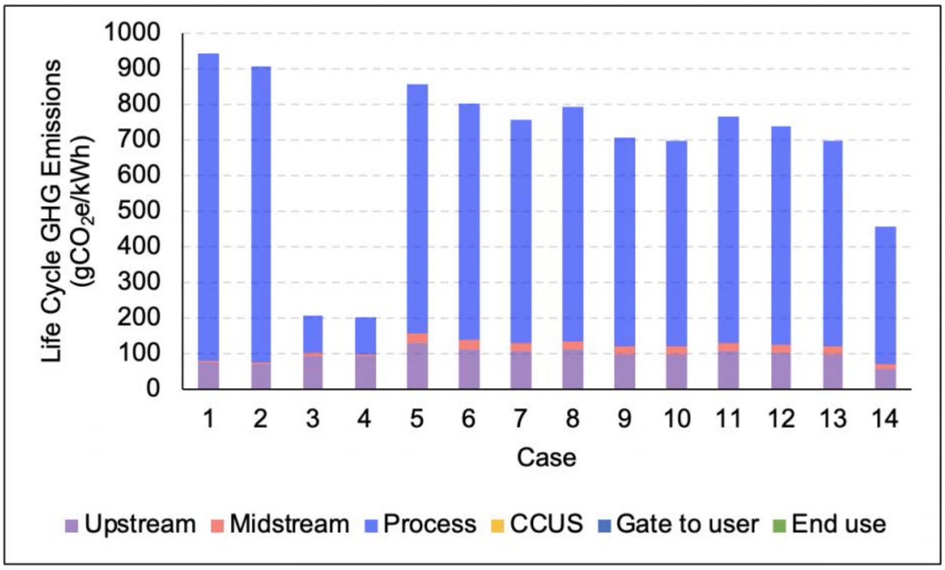

Figure 10 Summary of main power generation LCA results.

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).

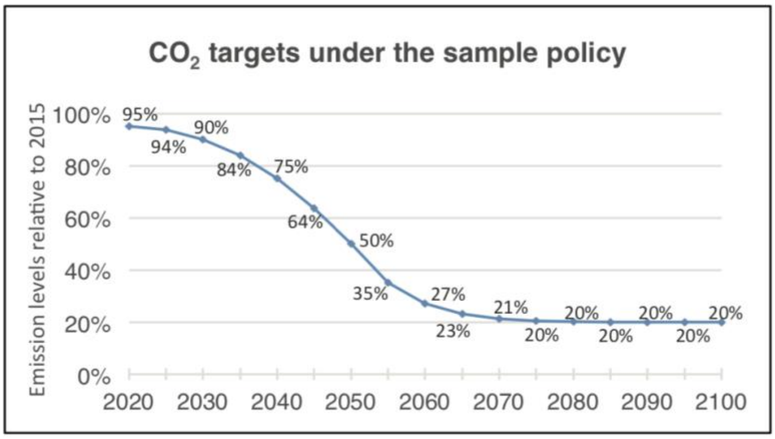

Figure 11 CO_2 targets under the sample policy.

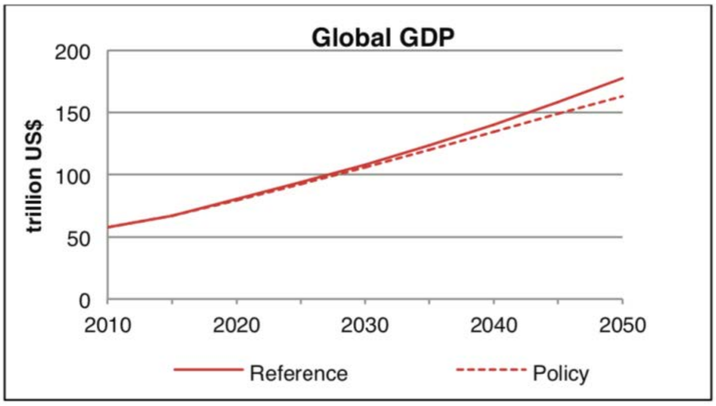

Figure 12 Global GDP: BAU vs. Policy.

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.

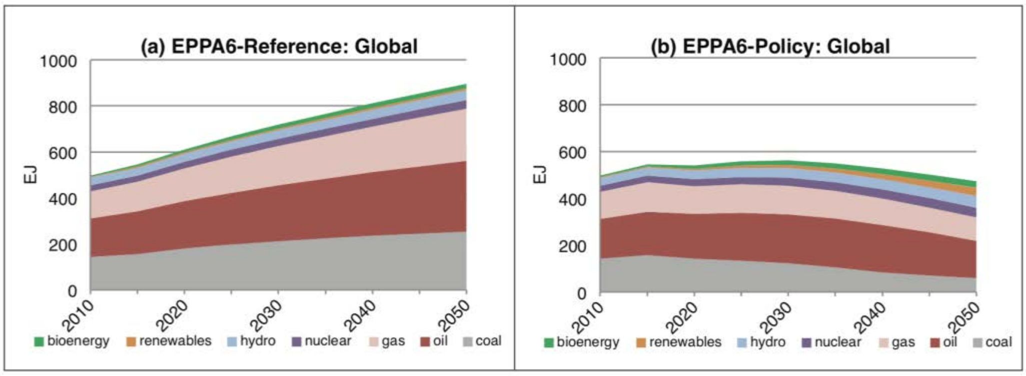

Figure 13 Total primary energy demand: (a) BAU vs. (b) Policy.

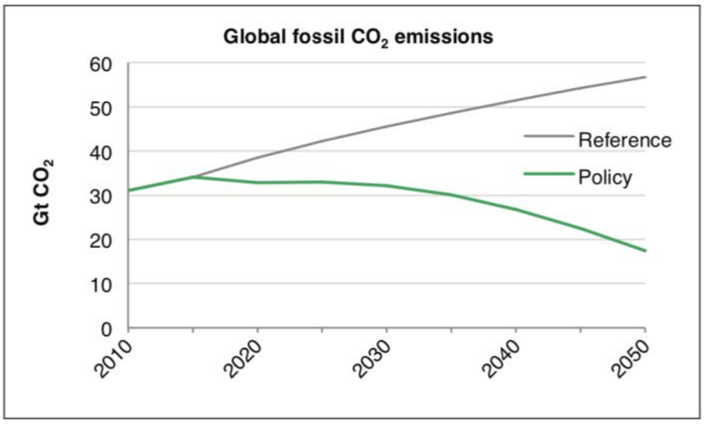

Figure 14 Global fossil CO_2 emissions.

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.

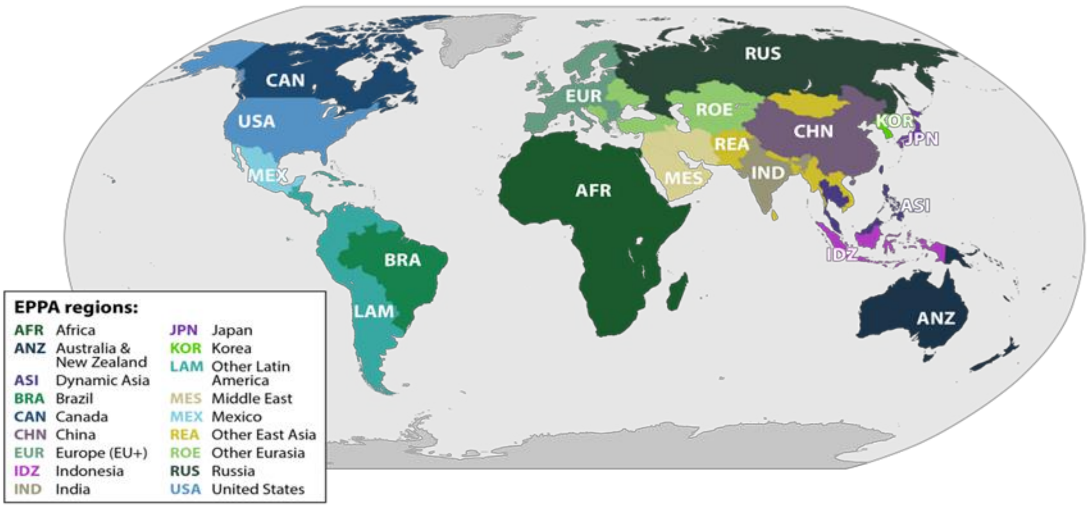

Figure 15 Regional representation in the EPPA model.

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

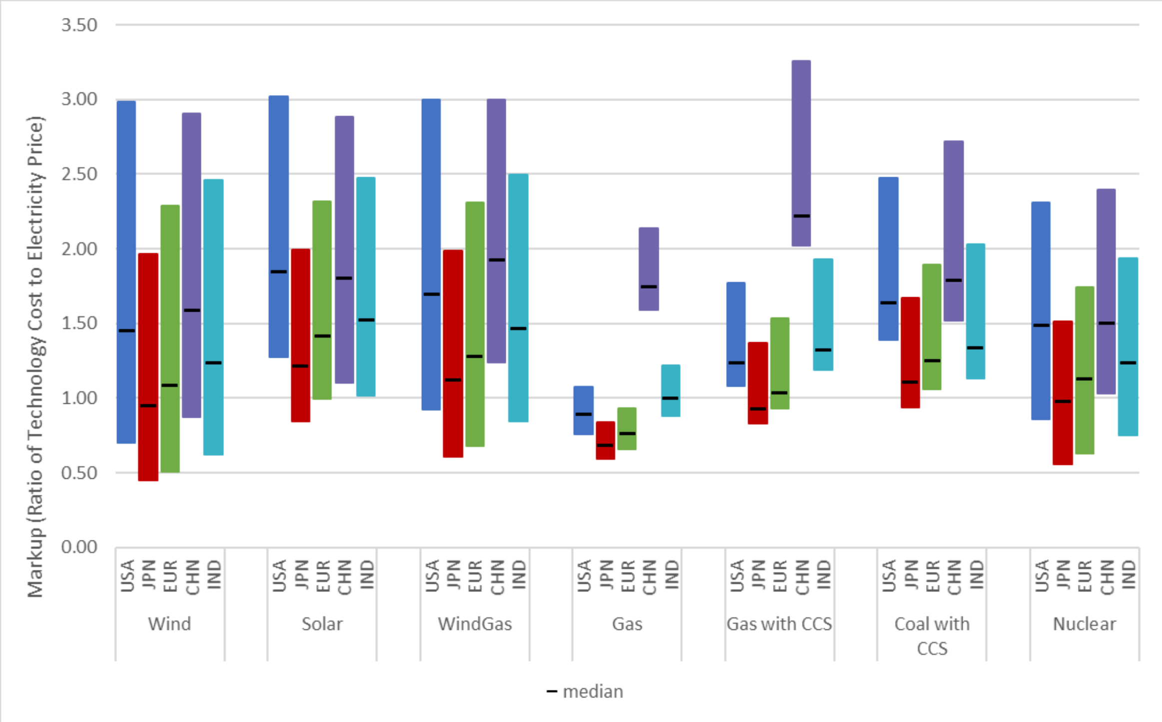

Figure 16 Markup range and median for a set of technologies in major regions. The colored bars represent the range using min and max data from IEA (2015), with the black line representing the median, which is used as the base markup. Markup values above 1 mean the cost of electricity generation from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

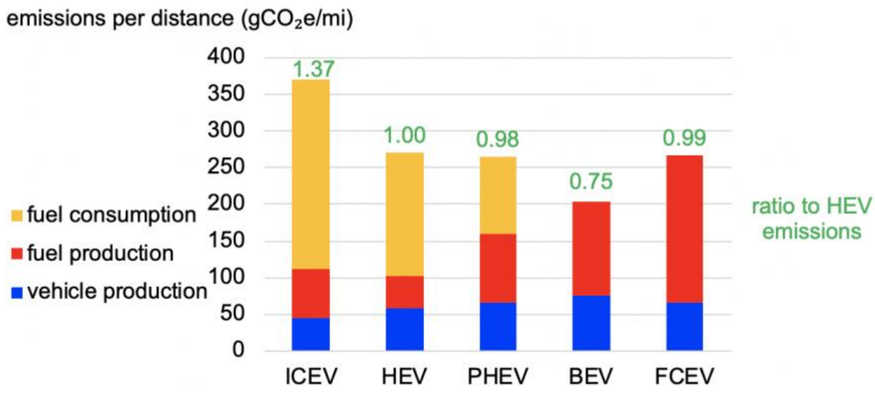

Figure 17 Lifecycle GHG emissions per mile for mid-size sedans with different powertrains, U.S. 2018 (note: depending on the input assumptions, the LCA results will change.)[1].

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.

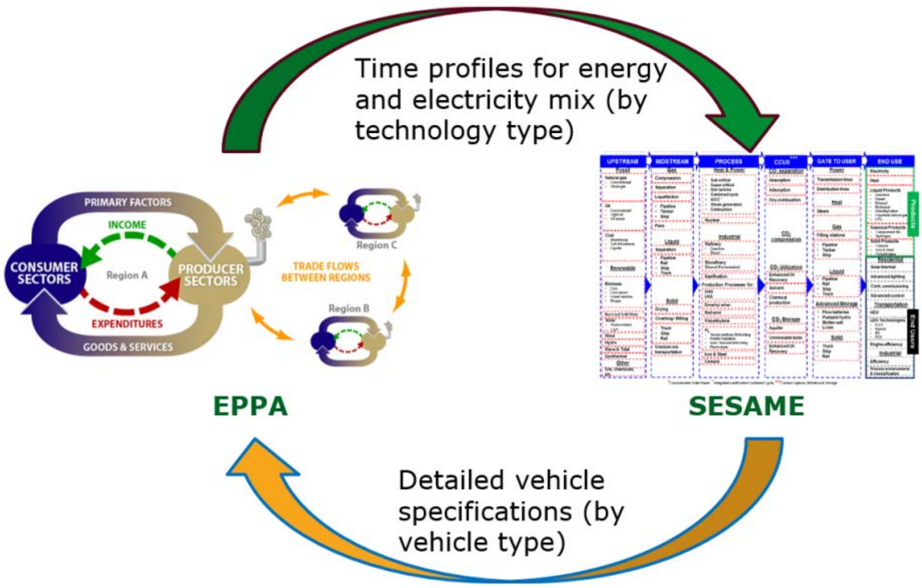

Figure 18 Illustrative diagram of information flows between EPPA and SESAME for an analysis of personal mobility. Similar flows can be established for other sectors.

<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.

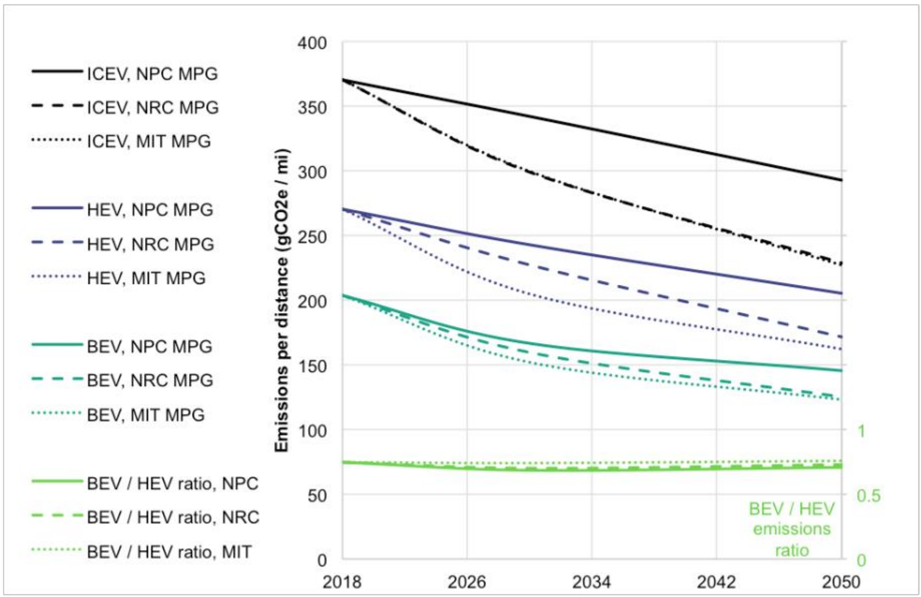

Figure 19 Vehicle emissions in the U.S. given different MPG projections.

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.

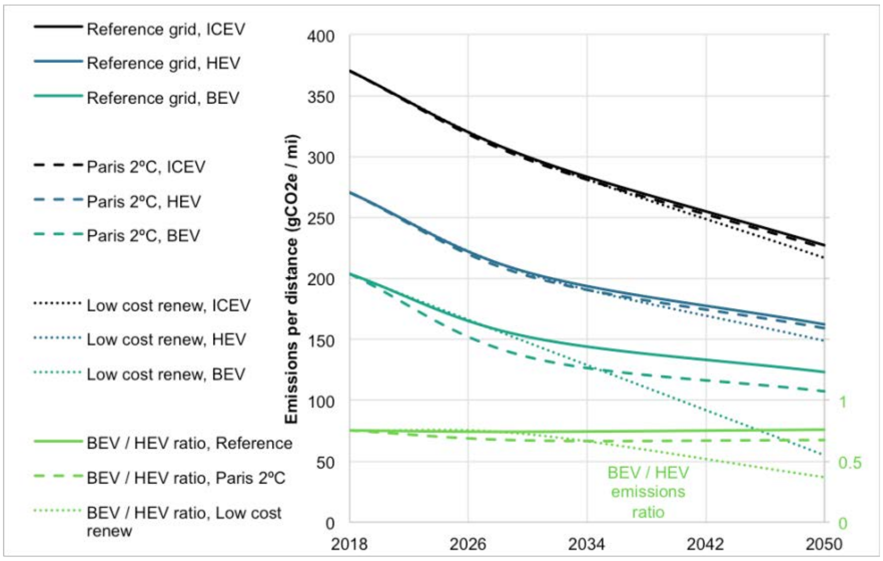

Figure 20 Vehicle emissions in the U.S. given different power grid projections.

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.

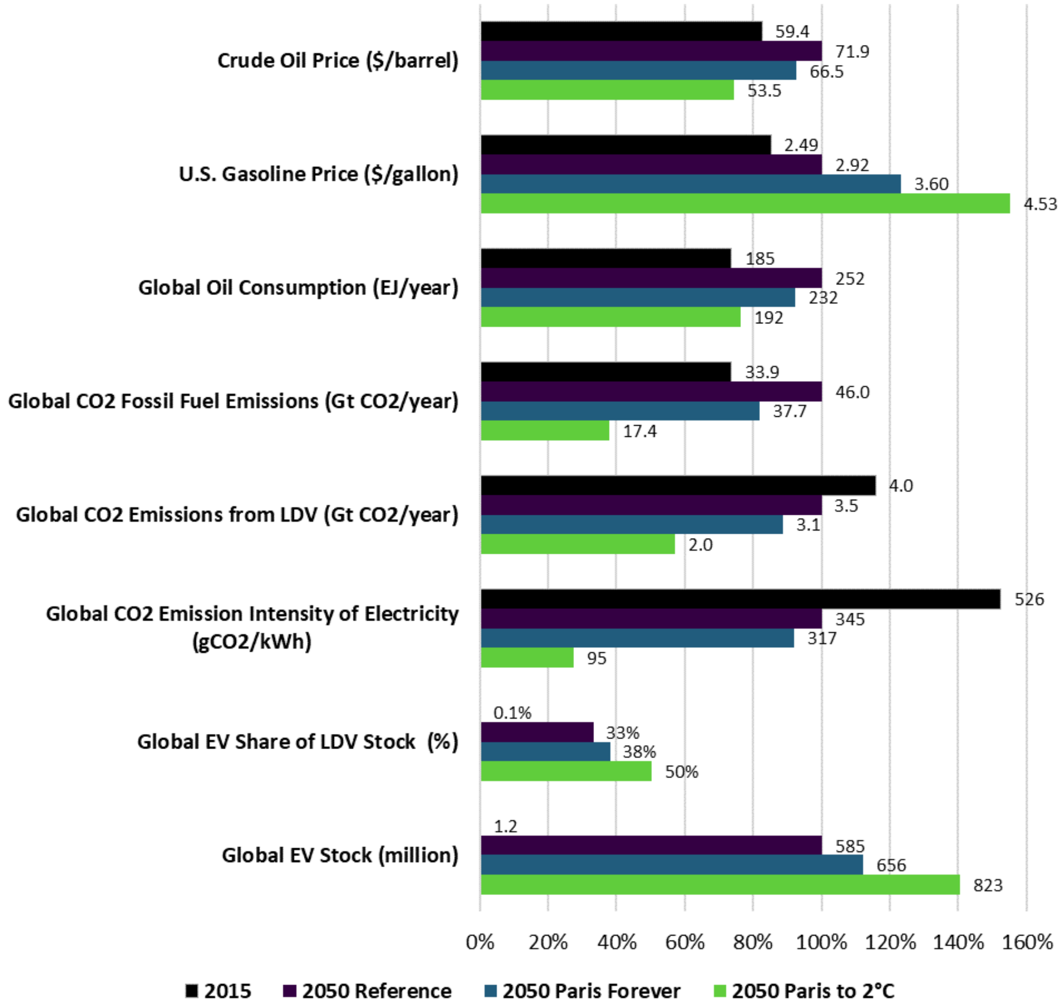

Figure 21 Major impacts of modeled climate scenarios in 2050 (2015 values are provided as reference).

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.

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Fabrice Devaux	Total S.A.
Jae Edmonds	PNNL
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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		

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Exploring the effects of California's COVID-19 shelter-in-place order on household energy practices and intention to adopt smart home technologies

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ABSTRACT

To contain the spread of the novel coronavirus (COVID-19), local and state governments in the U.S. have imposed restrictions on daily life, resulting in dramatic changes to how and where people interact, travel, socialize, and work. Using a social practice perspective, we explore how California's Shelter-in-Place (SIP) order impacted household energy activities. To do so, we conducted an online survey of California residents (n = 804) during active SIP restrictions (May 5–18, 2020). We asked respondents about changes to home occupancy patterns and household energy activities (e.g., cooking, electronics usage) due to SIP restrictions, as well as perspectives toward smart energy technologies. Households reported increased midday (10am–3pm) occupancy during SIP, and this increase is related to respondent and household characteristics, such as education and the presence of minors in the home. Examining change in the frequency of household activities during SIP, presence of minors and increased midday occupancy proved important. Finally, we considered relationships to intention to purchase smart home technologies, with the presence of minors and increased activity frequency relating to greater intention to purchase. These findings demonstrate how household activities and occupancy changed under COVID restrictions, how these changes may be related to energy use in the home, and how such COVID-related changes could be shaping perspectives toward smart home technology, potentially providing insight into future impacts on household practices and electricity demand.

1. Introduction

The 2019 coronavirus disease outbreak (SARS-CoV-2)—commonly referred to as coronavirus, COVID or COVID-19—has impacted global society at a scale and scope that is unparalleled in the post-World War II era. In the United States, the virus has exacted a devastating human toll, with over 230,000 deaths attributable to the disease as of November 2020 [1]. To protect populations from the spread of this highly virulent disease, many states, counties, and municipalities across the U.S. have responded with policies that restrict human movement and interaction. Such restrictions have led to lost jobs and closed businesses, disruptions to daily routines, and reduced social contact. Substantial variation exists in when states and communities imposed such COVID-related orders, the content of these orders, the duration of the orders, and what they are called (e.g., Shelter-in-Place, Stay at Home, Healthy at Home) [2]. Yet, one common result of the pandemic is the increased confinement of people within their respective localities. These restrictions—even as they are loosened or tightened—as well as voluntary actions people have taken to protect family members and the community, have resulted in substantial disruptions to the rhythms of daily life, altering everything from where people work, shop, eat, and travel to how they educate children, care for the elderly, and socialize with family and friends. While there are many consequences to these disruptions (e.g., increased remote work and learning; reduced social interaction; financial loss; mental health impacts), one little explored area is how COVID-19 is changing everyday routines and practices within the home environment [3]. Everything from when, how, and who performs activities in the home (e.g., food preparation, office work, leisure/recreation) and the intensity, duration, or timing of activities are likely undergoing rapid changes. These changes to activity patterns, especially for activities that use devices or appliances, could be substantially altering energy usage patterns in the home, potentially in ways that may persist even after the health crisis subsides.

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1.1. A social practice perspective on household energy use

Social scientists have long recognized that energy is used to fulfill specific household needs, e.g., for cleanliness, comfort, nourishment, entertainment, etc. [4,5]. The pandemic and associated restrictions are changing when, where, and how these needs are fulfilled – upending routines and concentrating many activities in the home. Social practice theory—which considers practices as the primary unit of analysis [6]—has become more and more commonplace in studies of household energy use [7–9]. A practice is defined as "a routinized type of behavior" (p. 249) [6] and consists of four main elements: "*common understandings* about what the practice means and how it is valued, *rules* about what procedures and protocols must be followed and adhered to, *practical knowledge* about how to carry out and perform a practice, and *material infrastructure*—or the 'stuff' that makes the practice possible, sensible and desirable" (p. 228) [10].

Typically, studies of how energy practices evolve and change over time have focused on longer time horizons (e.g., the widespread adoption of air conditioning) [4,10,11]. A noted exception has been studies of the effect of blackouts, fuel crises and more predictable disruptions like variable electricity pricing on everyday practices and routines. We explore how practices may have changed in a relatively short period of time in relation to a non-energy-related crisis: the COVID-19 pandemic and associated government restrictions. Past studies of energy-related disruptions on household energy practices have revealed, "the temporal fragility of habits and the elasticity of everyday life" (p. 68) [12], as people demonstrate their ingenuity and skill in restructuring and innovating daily routines [10]. What changes in routines and practices are households making in response to COVID-19 and associated government restrictions? Are particular types of households more or less affected? A social practice perspective allows us to focus on how the conventions and routines that comprise total energy consumption may be shifting rapidly in these unprecedented times.

New research suggests that COVID-19 and associated government restrictions are impacting energy production and consumption at a global scale [13–17], leading to a temporary decrease in global carbon emissions that is attributable to the pandemic [18]. Such findings suggest that opportunities may exist within this crisis for helping ease the transition towards a cleaner, lower emissions energy future. Smart home technologies, or "devices that provide some degree of digitally connected, automated, or enhanced services to building occupants" (p. 1), become particularly salient in this regard because these technologies are anticipated to play an important role in realizing this transition [19]. From a social practice perspective, smart home technologies affect the material infrastructure of practices. They can quantify and provide feedback, as well as automate and possibly enhance practices. At the same time, they can also be sources of frustration when too complicated or unreliable (and can be disruptive in their own right) [20]. Critically for our study, the use of these technologies is reliant on household adoption [21,22]. As a result of COVID-19, many households are undergoing abrupt and potentially lasting changes to their in-home lifestyles. Such experiences could shape perspectives toward smart technologies in the home.

1.2. The California context

California provides a unique setting for our study. While there is substantial state-level variation in renewable energy production and policies intended to increase adoption of smart home technology and distributed energy resources (DER), California has been on the forefront of both. It leads the country in renewable energy generation and policies that promote building energy efficiency standards, many of which include integration of smart home technologies [23]. Additionally, California was the first state to impose COVID-19 home confinement restrictions. With this in mind, we use the California context to explore the potentially dramatic changes that COVID-related restrictions have had on household occupancy and energy activities, as well as perceptions toward smart home energy technologies. In this research, we focus on the early stages of California's pandemic response, spanning from March to May 2020.

Along with a handful of U.S. states taking similar action in early March 2020 to confront the threat of COVID-19, California's governor, Gavin Newsom, declared a State of Emergency on March 4, 2020, following a rise in cases and California's first official coronavirus death [24]. Early restrictions in the first two weeks of March included bans on gatherings of a certain size and some school closures [25,26]. However, it was not until a rapid increase in COVID-19 cases in Santa Clara County that, on March 17, six San Francisco Bay Area counties (Alameda, Contra Costa, Marin, San Francisco, San Mateo, Santa Clara) and the City of Berkeley declared a Shelter-in-Place public health order, the first of its kind in the U.S. This order affected nearly 6.7 million California residents and required people to stay at home and only engage in essential activities and travel [27]. Additional counties followed suit, with the Governor ultimately declaring a California-wide stay at home directive by Executive Order on March 19, effectively limiting all nonessential travel and activities with exemptions for operations and activities deemed critical [28]. The first stage of the order, active from March 19 – May 7, imposed the strictest restrictions on travel and activities. On May 8, some of these restrictions were eased for low-risk businesses that were able to follow social distancing guidelines [29]. Throughout this research, we refer to this collection of COVID-19 restrictions in California during the March–May 2020 period of the pandemic response as Shelter-in-Place (SIP) orders.[1]

The first stage of the SIP orders mandated abrupt and substantial changes in where and how people interacted – changes that may persist after the pandemic has ended. At aggregate scales, these mandated restrictions, as well as voluntary behavioral changes to limit the spread of COVID-19, have already been observed through changes in human mobility patterns (e.g., travel to and from common destinations, such as home, work, retail shopping, etc.) and electricity consumption. California mobility trends related to retail, recreation and public transit decreased by 40% or more during SIP orders, while movement within residential environments (i.e., people staying home) increased by 12% [31]. Electricity usage at the grid level in California also experienced major changes with an estimated 8% decrease in electricity demand during April 2020, the height of active COVID-restrictions in the state [32]. However, the link between these aggregate measures and effects observed at smaller scales, such as the individual- and household-level, is lacking. This is the gap our work is intended to fulfill: linking COVID-19 restrictions to occupancy, activity levels, and preferences for energy-related technologies.

1.3. Research questions

By design, compliance with SIP orders should result in longer periods of time spent indoors at home. Before SIP orders, work, school, and other routinized activities, as well as recreation, exercise, and leisure, often led people outside the home throughout the day, and during SIP orders patterns of household occupancy likely changed. Understanding changes in active occupancy is particularly important in this regard as it not only reflects the changes that households are experiencing but also is consistently linked to residential energy consumption [33]. We therefore posit the following research question:

[1] Throughout this research, we have made the decision to refer to California's COVID-related restrictions as Shelter-in-Place (SIP) orders, as SIP orders were imposed before the statewide stay home order and are still active in many counties [30]. Furthermore, the term Shelter-in-Place was used by many media outlets during this time to refer to California's COVID-related restrictions more generally.

RQ1. *How did SIP orders impact residential occupancy patterns?*

Relatedly, many activities that may have typically occurred outside the home before COVID-19 (e.g., work, education, leisure, etc.) occurred within the home during SIP, with employees connecting remotely to their workplaces, school programs being taught online, and nightly entertainment in living rooms rather than movie theaters. We know from previous studies that understanding the timing and pattern of these activities can be important predictors of health, energy and other sustainability-related outcomes [9,34]. For example, eating meals at home is likely more frequent during SIP, which could lead to increased food preparation and cooking activities within the household or more use of food delivery services and takeout. We also know that many activities within the home can be related to energy consumption, for example, cooking hot meals has been found to be associated with higher electricity usage [33]. This has implications not only for how lifestyles have changed in the home due to changes in the intensity and frequency of activities, but for how households consume energy, depending on shifts in energy and/or non-energy using activities. Other work has found changes in self-reported energy use patterns during COVID-19, with higher than average electricity usage overall and a flattening of morning and evening peaks during weekdays [3]. We therefore offer the following research question:

RQ2. *How did SIP orders alter residential energy and non-energy related activities?*

Given some of the abrupt changes to daily lifestyles within home environments due to SIP orders, people likely had new experiences that influenced their perceptions about how to meet new and changing needs through technology. Research has shown many reasons why households may be more or less likely to adopt certain smart home technologies [3,21], [35–37.] They could be attuned to its benefits – e.g., energy savings, convenience and controllability, cost savings, and system benefits for the energy grid – but also concerned about its risk – e.g., privacy, security, technical reliability, and usability [19]. Much of this research considers the psychological and technical reasons for adoption. Yet, how perceived benefits and barriers to adoption may interact with a disruptive event like the COVID-19 pandemic and resultant restrictions have received little attention. One exception is a study that examined intention to adopt home energy management systems (HEMS) in New York, finding higher willingness-to-pay for groups of individuals with a moderate perceived level of risk for COVID-19 infection [3]. We thus offer the following research question:

RQ3. *How did SIP orders influence intention to adopt smart home technologies?*

Some households may have experienced more change under SIP orders than others. For example, families with children are now required to provide a variety of child-related services during weekdays at home due to the closure of many schools, daycares, camps, etc. Additionally, recent work exploring consumer spending patterns in the early stages of the pandemic found that households with children tended to spend more, also suggesting potential heterogeneity in impacts of the pandemic [38]. Prior research has also found that everything from residential building type to characteristics of individuals within the household to occupancy patterns can be related to electricity use in the home [39–43]. Given that these are important considerations for both the public and policy makers alike, we offer the following question:

RQ4. *How did household characteristics shape occupancy, activities, and energy-technology preferences during SIP orders?*

To address these research questions, we fielded an online survey to residents of California under active COVID-19 SIP orders. This approach is described in detail below.

2. Methods

2.1. Data collection

To better understand the impacts of SIP orders on household occupancy, energy activities and smart home adoption intention, we created a survey instrument administered to a panel of online participants from California. Participants were recruited by the survey research firm Qualtrics, and the survey was fielded from May 5 – May 18, 2020. While not a probability-based sample, all invited survey participants were located within California and recruited to match California-wide demographic estimates of gender, age, and educational attainment in the American Community Survey (ACS, 5-year estimates, 2013–2018) [44]. In total, we received 804 completed surveys. Respondents matched the ACS estimates within one percentage point for the target categories of gender, age, and education (see Table 1). While we did not purposively match on respondents' household characteristics, respondent households were similar to California ACS estimates. With respect to household income (*survey* median $60,000 - $69,999 vs. *ACS* median $71,228), size of household (*survey* average 2.8 vs. *ACS* average 3.0), and households with minors (*survey* 28.6% vs. *ACS* 34.8%), our sample was below ACS estimates. For single-family housing (*survey* 64.7% vs. *ACS* 57.9%) and owner-occupied housing (*survey* 56.1% vs. *ACS* 50.3%), our sample was above ACS estimates. For these household characteristics, differences between our survey respondents and California ACS population statistics did not exceed 7%.[2]

2.2. Measures

2.2.1. Change in midday occupancy on weekdays due to COVID-related restrictions

To measure change in midday weekday occupancy during SIP orders, we first asked respondents "Before your household made any changes due to shelter-in-place orders related to COVID-19 (coronavirus) and excluding pets, how often is someone at home during the day (10am –

Table 1
Comparison of survey respondent and household characteristics to American Community Survey estimates for California (5-year estimates, 2013–2018).

Measure	Survey Respondents	California ACS 2018 (5-year Estimates)
Gender	Male: 50.0% Female: 49.9% Other: 0.1%	Male: 49.7% Female: 50.3%
Age[a]	18-34: 31.8% 35-64: 50.4% 65 and over: 17.8%	18-34: 32.5% 35-64: 49.9% 65 and over: 17.7%
Education	High school or less: 37.8% Some college: 29.1% Bachelor's or higher: 33.1%	High school or less: 37.7% Some college: 29.1% Bachelor's or higher: 33.3%
Income	Median household income category: $60,000 - $69,999	Median household income: $71,228
Average household size	2.85	3.0
Households with minors	Households with one or more people under 18 years old: 28.6%	Households with one or more people under 18 years old: 34.8%
Housing type	Single family home: 64.7%	Single unit detached: 57.9%
Owner occupied household	56.1% owner-occupied	50.3% owner-occupied

[a] California ACS 2018 estimates for age were adjusted for comparison to the survey sample which did not include participants under 18 years old.

[2] This does not include household income where we only have a category range for comparison.

3pm) on weekdays (Monday – Friday)?" on a scale from 1 = "Never" to 6 = "5 days a week", and then asked this same question with a modification to elicit midday occupancy during SIP ("Since your household made changes due to shelter-in-place …"). We then calculated the difference in midday occupancy before SIP (mean = 3.611 days; sd = 1.955) and during SIP (mean = 4.284 days; sd = 1.556) to generate a change in midday weekday occupancy metric (During SIP – Before SIP; mean = 0.6729 days; sd = 1.591). See Appendix A.1 Figure A.1 for the distributional characteristics of this measure.

2.2.2. Change in household activities due to SIP orders

We next measured change in household activity frequency during SIP orders using the following question: "Since the shelter-in-place orders related to COVID-19 (coronavirus), are you and members of your household doing the following things more often, less often or about the same?". Response items included: "Eating together", "Cooking with a stove top/range or oven", "Running the dishwasher", "Doing laundry using a washing machine or dryer", "Using a computer, game console, tablet, or TV", "Using electric heating when it's cold or a fan/AC when it's hot", "Being physically active outdoors", "Being physically active indoors on devices that use electricity", "Communicating by phone or video", and "Turning on lights". Each of these items was situated on the following three-point scale: -1 = "Less often"; 0 = "About the same amount"; and 1 = "More often". We then use these items to create two additive measures of activity: (1) change in the frequency of all household activities (mean = 2.876; sd = 3.395) and (2) change in the frequency of all household *energy* activities (mean = 2.678; sd = 3.018).

2.2.3. Intention to purchase smart appliances and devices

The final measure that we considered was a respondent's intention to purchase a smart appliance or device. We asked, "Which statement best describes your household's intentions to purchase the following items?". Response items included: "Solar panels that generate electricity", "Smart thermostat (Nest, Ecobee, etc.)", "Smart appliances (Samsung Family Hub refrigerator, Bosch Home Connect dishwasher, etc.)", "Home Energy Monitoring System (HEMS) (Sense, CURB, etc.)", "Home energy storage battery (Tesla Powerwall, etc.), "Smart light bulbs (Philips Hue, etc.)" and "Smart plug or power strip". Response categories for these items were "We have already purchased", "We intend to purchase in the next 12 months", "We intend to purchase after 12 months", "We have no intention to purchase", and "This cannot be installed at our current home." We recoded these categories to 0 = "No intention to adopt" and 1 = "Intention to adopt", excluding items that had already been adopted. We then formed a smart technology adoption measure by summing each of the recoded items and dividing by the total number of non-adopted items.[3] This smart adoption measure ranged from 0 to 1 (mean = 0.34; sd = 0.29). See Appendix A.2-A.3 Figure A.2, Table A.3 for summary statistics and distribution.

2.3. Analysis

To explore the relationships between respondent and household characteristics, smart device/appliance adoption, midday occupancy, and activity frequency during SIP orders, we apply ordinary least squares regression models. Our analytical sample for regression modeling is 746, with missing data[4] deleted listwise. In our model specifications, we include household characteristics alongside respondent demographics. The reason for this is two-fold. First, we include the respondent characteristics of gender, age, and education because we used these categories for sample selection. Second, while these respondent characteristics do not necessarily describe complete household characteristics (except in the case of single occupant households or 19.4% of our sample), they do provide important insight into the characteristics of the household, such as educational achievement of a household member. In addition to survey respondent characteristics, we also include an indicator for whether minors are present in the home, the average household size during SIP, whether the home is owner-occupied, the type of housing (single family vs. other), and household income. Using these baseline model specifications, we test whether household dynamics, such as changes to midday occupancy and activity frequency due to SIP orders, may be related to intentions to adopt smart technologies.

3. Results

3.1. Change in occupancy related to COVID-19 SIP orders

Comparing midday occupancy before SIP and during SIP on weekdays, we find an increase in occupancy of approximately 0.67 days (Fig. 1; $p < 0.001$). While a majority of participants did not change midday occupancy (74.2%), the next most frequent category is 5 (7.7%), or a shift from no midday occupancy on weekdays before SIP to midday occupancy on every weekday during SIP (Appendix A.1, Figure A.1).

We next explore which households experienced the most change in midday (Table 2). We find that increased midday occupancy is associated with respondents who hold a bachelor's degree or higher ($\beta = 0.454$; $p < 0.01$) and households with higher income ($\beta = 0.558$; $p < 0.001$). In contrast, lower change in midday occupancy is associated with younger respondents ($\beta = -0.342$; $p < 0.01$), living in a single family home ($\beta = -0.287$; $p < 0.05$), and smaller households sizes ($\beta = -0.28$; $p < 0.05$) (Table 2: Model A1). Next we consider how the presence of minors (persons under 18 years old) in the home, many of whom may have typically been at school or childcare during weekdays before SIP, influences changes in midday occupancy (Table 2: Model A2). We find that minors are associated with an average increase in midday occupancy of approximately half a day ($\beta = 0.445$; $p < 0.01$). The inclusion of this variable does not substantially alter the sign or magnitude of other respondent or household characteristics (compared to Model A1).

3.2. Change in activity frequency due to COVID-19 SIP orders

For all household activities (Fig. 2), respondents reported a change in activity frequency that was statistically different from zero ($p < 0.05$), with all activities except for "Being physically active outdoors" occurring more often during SIP. The activities with the highest magnitude of change (over half of respondents reported them occurring more frequently under SIP) are "Using a computer, game console, tablet, or TV", "Cooking with a stove top/range or oven", and "Communicating by phone or video." Next, we consider the differential impact that having minors in the home has in reported changes in activities during SIP orders (Fig. 3). We find that, for almost all included activities (except "Using electric heating when it's cold or fan/AC when it's hot" and "Being physically active outdoors"), reported changes in activity frequencies for households with minors are significantly higher than those without ($p < 0.05$).

We now consider how respondent and household characteristics

[3] We combine "This cannot be installed at our current home" with "We have no intention to purchase" for two reasons. First, some participants may not make the distinction between "no intention to purchase" and "cannot be installed" because the reason they do not intend to purchase could be because it cannot be installed in their home. Second, we included "single family home" and "owner occupied home" in our modeling, and both of these household characteristics are related to the feasibility of installing some of these smart appliances/devices.

[4] The main source of missing data was respondents who do not wish to share their household income.

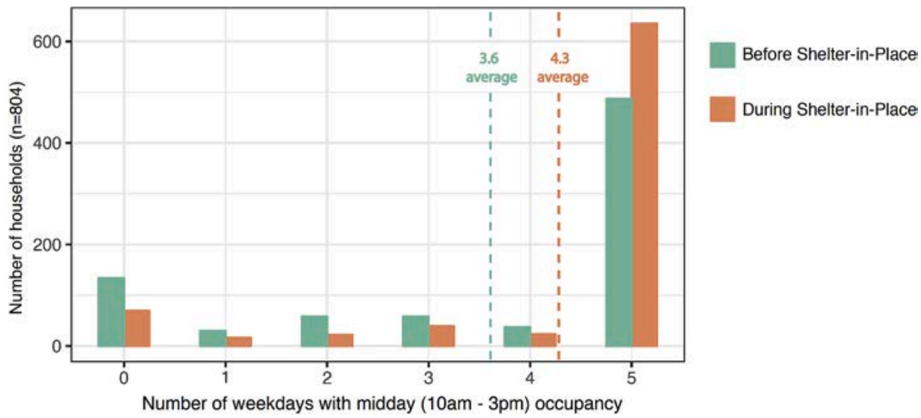

Fig. 1. Reported number of weekdays that the household was occupied from 10am to 3pm, before and during SIP orders.

Table 2
Odinary least squares regression models predicting change in midday weekday occupancy.

	Change in midday weekday occupancy	
	Model A1	Model A2
	Std. beta (p-value)	Std. beta (p-value)
Respondent characteristics		
Female (vs. male)	0.103 (0.376)	0.105 (0.364)
Age (categories)	−0.342** (0.007)	−0.341** (0.007)
Bachelor's or higher (vs. less than bachelor's degree)	0.454** (0.001)	0.457** (0.001)
Household characteristics		
Household income	0.558*** (<0.001)	0.524*** (<0.001)
Single family home	−0.287* (0.020)	−0.294* (0.017)
Owner occupied home	−0.114 (0.392)	−0.088 (0.505)
Household size	−0.28* (0.029)	−0.516** (0.001)
Minors present (younger than 18 years old)		0.445** (0.004)
Intercept (unstandardized)	0.982** (0.001)	1.092*** (<0.001)
R-squared	0.085	0.095
N	747	747

Significance level: *p < 0.05; **p < 0.01; ***p < 0.001.

shape change in the frequency of these activities during SIP orders (Table 3). In the first set of models (Table 3: Models B1 and B2), we only include activities related to household energy use, excluding "Being physically active outdoors" and "Eating together." In the next set of models (Table 3: Models B3 and B4), we consider all activities. In Model B1, we find that respondents who are female (vs. male) ($\beta = 0.581$; $p < 0.01$), younger ($\beta =$ -1.42; $p < 0.001$), in higher income households ($\beta = 0.891$; $p < 0.001$) and households with minors ($\beta = 0.737$; $p < 0.05$) report increases in energy-related activity frequency during SIP orders. We also find that the sign and magnitude of these estimates are consistent for all activity frequency models (Table 3: Models B1–B4). We next consider the role that change in midday occupancy plays in reported activities. We find that households who report increased midday occupancy on weekdays also reported increases in the frequency of both energy-related activities ($\beta = 0.875$; $p < 0.001$) and all activities ($\beta = 0.968$; $p < 0.001$) (Table 3: Models B2 and B4).

3.3. Relationship between COVID-19 SIP orders and intention to adopt smart home technologies

Lastly, we investigate the impact that changes in occupancy and

Table 3
Ordinary least squares regression models predicting change in the frequency of energy-related activities and change in the frequency of all included activities.

	Change in frequency of energy-related activities		Change in frequency of all activities	
	Model B1	Model B2	Model B3	Model B4
	Std. beta (p-value)	Std. beta (p-value)	Std. beta (p-value)	Std. beta (p-value)
Respondent characteristics				
Female (vs. male)	0.581** (0.006)	0.553** (0.008)	0.638** (0.006)	0.607** (0.009)
Age (categories)	−1.420*** (<0.001)	−1.327*** (<0.001)	−1.694*** (<0.001)	−1.592*** (<0.001)
Bachelor's or higher (vs. less than bachelor's degree)	0.568* (0.018)	0.444 (0.064)	0.751** (0.005)	0.614* (0.021)
Household characteristics				
Household income	0.891*** (<0.001)	0.75** (0.002)	1.078*** (<0.001)	0.921** (0.001)
Single family home	0.082 (0.715)	0.161 (0.469)	0.33 (0.184)	0.418 (0.091)
Owner occupied household	−0.099 (0.681)	−0.075 (0.753)	−0.138 (0.607)	−0.112 (0.674)
Household size	0.206 (0.455)	0.346 (0.209)	0.231 (0.451)	0.385 (0.208)
Minors present (younger than 18 years old)	0.737* (0.010)	0.617* (0.029)	0.888** (0.005)	0.754* (0.016)
Midday occupancy change (weekdays)		0.875*** (<0.001)		0.968*** (<0.001)
Intercept (unstandardized)	3.357*** (<0.001)	3.062*** (<0.001)	3.597*** (<0.001)	3.271*** (<0.001)
R-squared	0.138	0.157	0.156	0.175
N	747	747	747	747

Significance level: *p < 0.05; **p < 0.01; ***p < 0.001.

activity measures during SIP, as well as respondent and household characteristics, have on intention to adopt smart technologies (Table 4).[5] In our baseline model specification, we find that respondents who are younger ($\beta =$ -0.109; $p < 0.001$), male (vs. female) ($\beta =$ -0.049; $p < 0.05$), in higher income households ($\beta = 0.062$; $p < 0.05$), and in households with minors ($\beta = 0.089$; $p < 0.01$) have more intention to

[5] For analysis that considers intention to purchase each smart home technology as a dependent variable in separate models, see Appendix A.4 - A.5. When we compare statistically significant respondent and household characteristics across these separate smart technology models, we find that estimates are consistent with findings from Table 4.

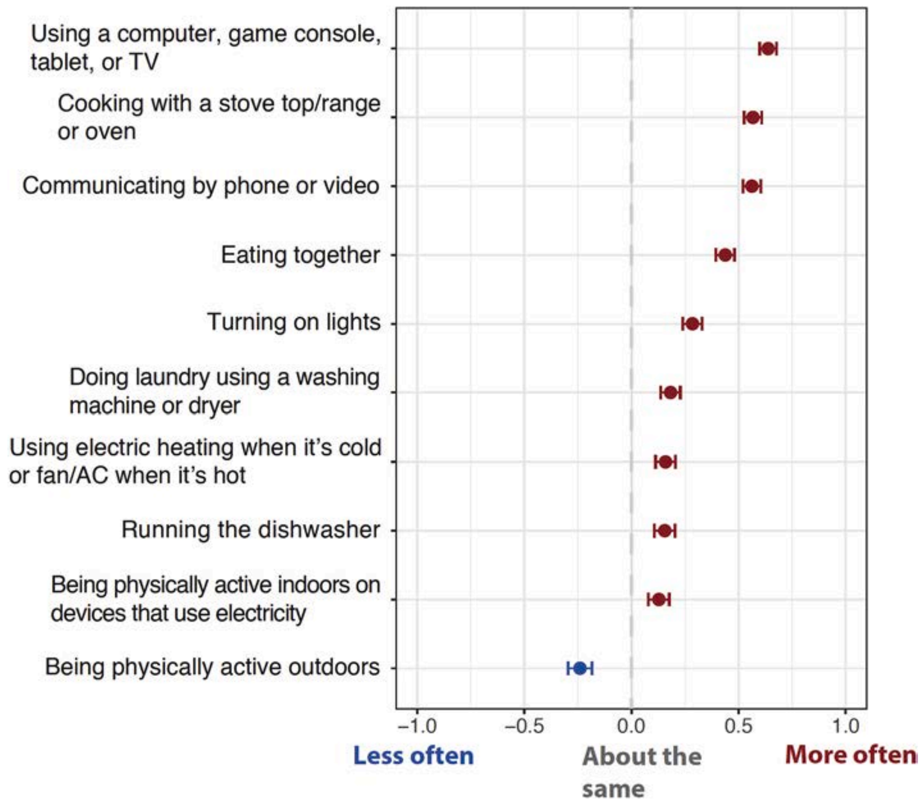

Fig. 2. Reported change in activities during SIP orders. Points represent means, lines 95% confidence intervals for a one sample *t*-test. All activity changes are statistically different from zero.

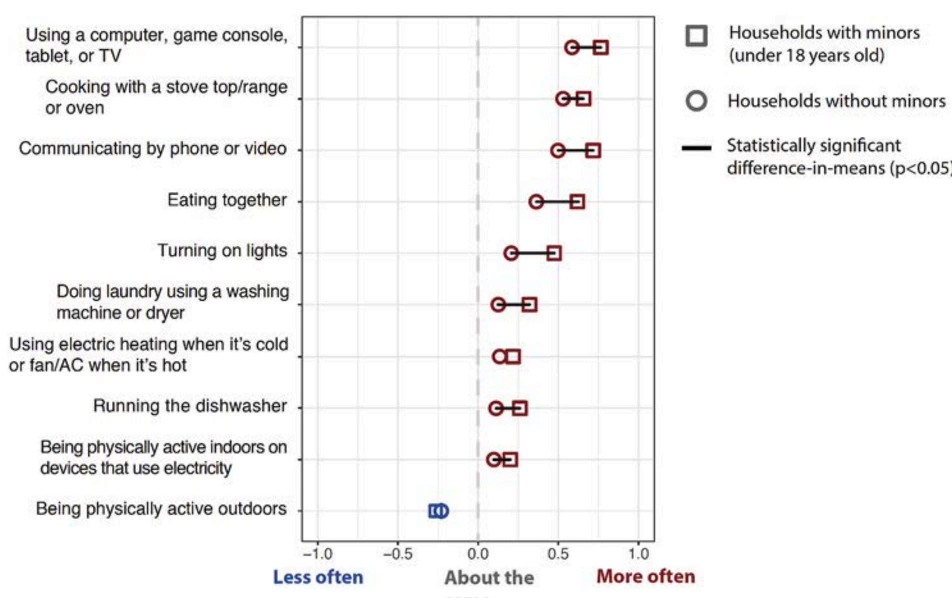

Fig. 3. Reported change in activities during SIP orders for households with minors and households without minors. Shapes represent means, and a dark line indicates that the difference-in-means between the two household groups is statistically significant ($p < 0.05$).

Table 4
Ordinary least squares regression models predicting intention to purchase smart appliances.

	Share of smart technology intention to purchase			
	Model C1	Model C2	Model C3	Model C4
	Std. beta (p-value)	Std. beta (p-value)	Std. beta (p-value)	Std. beta (p-value)
Respondent characteristics				
Female (vs. male)	−0.049* (0.019)	−0.050* (0.018)	−0.058** (0.006)	−0.058** (0.005)
Age (categories)	−0.109*** (<0.001)	−0.107*** (<0.001)	−0.088*** (<0.001)	−0.084*** (<0.001)
Bachelor's or higher (vs. less than bachelor's degree)	0.009 (0.719)	0.006 (0.806)	−0.000 (0.995)	−0.002 (0.917)
Household characteristics				
Household income	0.062* (0.010)	0.059* (0.015)	0.048* (0.047)	0.046 (0.060)
Single family home	−0.002 (0.941)	0.000 (0.998)	−0.002 (0.923)	−0.006 (0.794)
Owner occupied household	0.004 (0.854)	0.005 (0.837)	0.006 (0.798)	0.007 (0.780)
Household size	−0.017 (0.533)	−0.014 (0.610)	−0.019 (0.491)	−0.019 (0.477)
Minors present (younger than 18 years old)	0.089** (0.002)	0.086** (0.003)	0.077** (0.006)	0.075** (0.008)
Midday occupancy change (weekdays) during SIP		0.019 (0.381)	0.006 (0.766)	0.005 (0.816)
Change in frequency of energy-related activities during SIP			0.085*** (<0.001)	
Change in frequency of all activities SIP				0.096*** (<0.001)
Intercept (unstandardized)	0.479*** (<0.001)	0.473*** (<0.001)	0.429*** (<0.001)	0.426*** (<0.001)
R-squared	0.080	0.081	0.100	0.104
N	746	746	746	746

Significance level: *p < 0.05; **p < 0.01; ***p < 0.001.

purchase smart technology (Table 4: Model C1). When change in midday occupancy during SIP is added to this model specification (Table 4: Model C2), we do not observe statistically significant effects. However, when we add change in the frequency of energy activities during SIP (Table 4: Model C3), those who report higher changes ($\beta = 0.085$; $p < 0.001$) also express greater intention to adopt smart technologies, at a magnitude similar to age (the highest magnitude characteristic in Model C1 and C2). We find even stronger effects when we apply the activity frequency measure that includes all activities ($\beta = 0.096$; $p < 0.001$; Table 4: Model C4).

5. Discussion and conclusions

We find broad evidence that Californians in our sample spent more time at home during the middle of the day (10am – 3pm) on weekdays under SIP orders (RQ1), with average midday occupancy increasing by approximately half a day per five-day week (Monday-Friday). Reported midday occupancy was already high in our sample before SIP (on average, 3.6 days per week), so there was not much room for additional increases in occupancy during SIP orders. Larger households were less likely to report changes in midday occupancy during SIP. However, households with minors were, reflecting how patterns of school-aged children have changed from being away at school to being home in the middle of the day. Such a finding suggests that households with minors experienced changes in household lifestyles and practices during SIP in a way that distinguishes them from other household compositions.

When examining changes in the frequency of household activities during SIP (RQ2), we find evidence that there is, on average, an increase in the frequency of reported activities, particularly for activities that use devices with a screen/display or are food-related. Moreover, there was an increase in all activities that were energy-related. These finding suggests that many practices are shifting to the home environment. And, while energy activities were the focus of this survey, non-energy-related activities, such as eating together, increased in frequency, while being physically active outdoors decreased. When we compare differences between households with minors to those without, we again find results reinforcing that families with minors experienced SIP orders differently and perhaps more intensively. For example, reported activity frequency is higher for households with minors for all activities apart from heating/cooling and exercising outside. In regression modeling, we find that the presence of minors is associated with an increase in reported activities. Other respondent characteristics—age, gender, income and education—are also associated with changes in activity frequencies. Our finding related to gender echoes media coverage of the differential impacts of SIP orders on household members – with women, and particularly mothers, viewed as taking on most of the increase in domestic and childcare responsibilities during COVID-related restrictions (many of which involve energy use) [45]. Additionally, when we include midday occupancy change during SIP in our model specification, it also has an impact on the frequency of activities during SIP. Such a result is consistent with our expectations: households that reported more midday occupancy also report higher activity frequency.

We now explore how SIP orders may reach beyond activities and occupancy to shape preferences toward and perceptions of smart home technology (RQ3). When we examine factors associated with the intention to adopt smart home technology, we find—consistent with the existing literature on smart home technologies [46]—that men, younger respondents, and higher income households have greater intentions to adopt. We also find that households with minors have higher intentions to purchase smart home technology. Additionally, while change in midday occupancy during SIP is not associated with intention to purchase smart technology, both reports of increased *energy-using activities* and *all energy and non-energy activities* are associated with greater intention to purchase such technologies. This suggests that while individual and household characteristics undoubtably have an impact on the intention to adopt smart technology, as shown in previous research [46], higher levels of reported activity frequency during SIP are also important. There are a few potential reasons why we would find this effect. First, households that are reporting more frequent household activities due to SIP may be looking for ways to automate and enhance their lives through some of the features that smart devices provide. Additionally, nearly all of the devices we asked about are associated with energy savings or efficiency, and some households could be looking toward these technologies to save money. Yet another reason is that, because people are at home and interacting with devices more frequently, they could be more motivated to improve their home environment by integrating smart technologies, perhaps even amplified through increased exposure to social media or advertisements while at home. While we did not consider smart home technologies unrelated to energy savings or efficiency, if the above is true, our expectation is that there could also be higher intentions to adopt devices that can enhance home environments in other ways (e.g., smart air purification systems). Future research is needed to better elucidate these links and the adoption of other types of smart technologies.

We also explored how differences in household characteristics may relate to behavioral and attitudinal responses during SIP orders (RQ4). Here, we found that household composition, as well as demographics, matter. Additionally, there has been much focus in the media around how households with minors have had challenges in adapting to SIP orders, with adults in the household taking on new roles as educators and childcare providers [47]. We see evidence that households with minors are experiencing SIP orders differently, even after controlling for other household and individual characteristics. These experiences for households with minors are associated with greater home occupancy during midday and more frequent energy-using activities.

Such patterns suggest that, overall, families with children may be facing potentially larger electricity bills and more time constraints, two reasons why respondents from these households may have higher intentions to adopt smart technology. However, acquiring these technologies can be expensive, perhaps prohibitively so for families on tight budgets or facing new income insecurity due to the impacts of COVID-19. Some of these barriers may be reflected in our findings that higher income households are associated with greater intention to adopt smart technologies. We also see some changes in family lifestyles during SIP orders that are associated with healthier lifestyles, such as respondents reporting prepping meals at home and eating meals together more often [48]. This finding indicates that practices associated with cooking may be been particularly affected in this crisis. At the same time, other reported activity frequency changes are less healthy – e.g., reduced outdoor exercise and increased screen time – as indicated by previous scholarship [49,50].

These findings support the preponderance of media reporting that society—and the practices and routines that underpin daily life—are undergoing substantial changes due to COVID-related restrictions. Our research considers a two-week window in May 2020, during which there were indications that some California SIP restrictions would be lifted in the near future. It is difficult to know whether our results would have been different if we had surveyed respondents earlier, perhaps a week after the first statewide order. When we conducted our poll, SIP orders had been in place for over a month. By this time, we expect some households were following a more regular daily routine. At the same time, polling directly after SIP in late March could have better captured immediate changes in household practices and lifestyles due to SIP orders. The immediacy of the disruption may have led our respondents to report even higher levels of perceived change. While it is difficult to unpack these specific dynamics, we believe that the timing of our survey struck an appropriate balance between when the SIP order was first imposed and the length of time the population was under this order.

Another challenge to conducting research about households is that it is individuals within these households that are sampled. To some extent we helped account for this by including the demographic characteristics we used for sampling in all our modeling specifications. However, unless the respondent is from a single occupant household, it will always be challenging to make claims about households using individual survey respondents. Given the similarity in composition of our sample to the California population and the obvious challenges of conducting a probability/address-based mail survey during active SIP orders, we feel that this online survey convenience sample approach was one of the best options among the limited options available to us at the time of the survey.

From a theoretical perspective, our results suggest many adjustments to everyday practices as a result of the disruptions caused by the pandemic and associated government restrictions. Such findings add a dimension to social practice theory not yet well documented in the literature, the element of change in practices. To date, practices are considered as stable, enduring, and relatively resistant to rapid, short term change. Adjustments in practices in this case appears more pronounced for households with minors. Whether practice-related adaptations to SIP remain in place after the pandemic is not yet known but offers intriguing avenues for future research. Our results also highlight the role of non-energy-related crises in shaping energy-related practices, suggesting another avenue of research for social practice scholars.

From a policy perspective, these changes in activity and occupancy during SIP orders suggest that households are likely demanding more energy, particularly electricity, and at different times of day. These increases in electricity demand may impact households differentially, with households with minors facing increased energy bills and possible energy insecurity. Such inequalities may be exacerbated if these increases in electricity use correspond to times of day when electricity rates are higher (e.g., time of use pricing) and economic prospects remain uncertain [51]. On the other hand, we find evidence that SIP orders may also be influencing intention to purchase smart home technologies in many of the same types of households that have been differentially impacted. In this sense, the pandemic and associated restrictions could serve as a focusing event that places new attention on the relationship between household activities and energy use, helping people realize the importance of smart home technologies—for those that can afford them—in a transition toward a greener and cleaner grid.

It is important to note the exploratory nature of this research, which provides a static snapshot of a highly dynamic and continually evolving pandemic response. We conducted this study during the height of California's initial Shelter-in-Place orders, which represents some of the most stringent COVID-related restrictions in California to date. And while some of these restrictions have been lifted, there are indications that the United States, as of November 2020, is entering a new, and perhaps deadlier, phase of the pandemic [52]. In this respect, our research could be particularly informative for understanding the effects of tighter restrictions on households, while also providing a lens to view future impacts as areas across the world adjust the intensity of their pandemic response.

Credit author statement

Chad Zanocco: Writing - original draft, Conceptualization, Methodology, Formal analysis, Visualization. **June Flora:** Conceptualization, Methodology, Writing - review & editing, Project administration. **Ram Rajagopal:** Conceptualization, Supervision, Funding acquisition. **Hilary S. Boudet:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

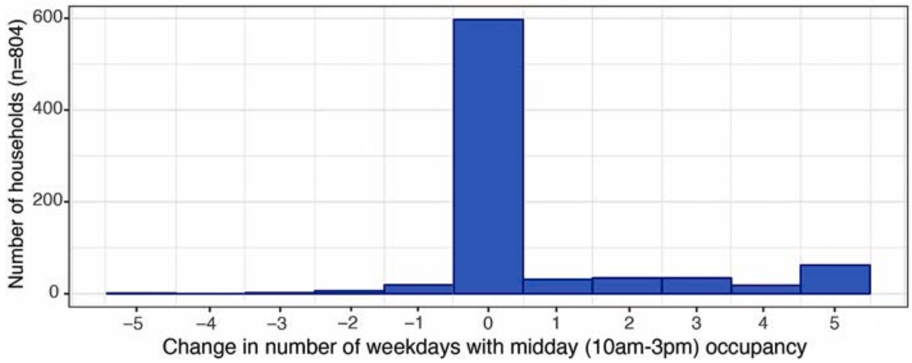

Fig. A.1. Distribution of change in midday (10am-3pm) occupancy on weekdays (during SIP – before SIP). Positive values indicate an increase in midday occupancy days related to SIP orders, negative values indicate a decrease in midday occupancy days related to SIP orders.

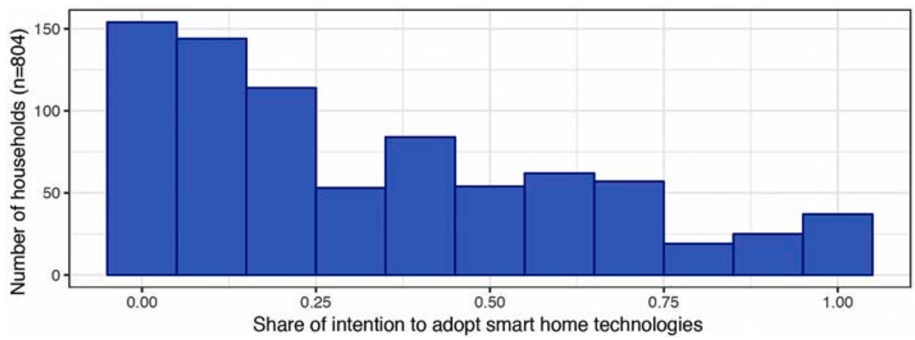

Fig. A.2. Distribution of intention to adopt metric for all respondents (n = 804) where 0 indicates no intention to purchase and 1 indicates an intention to purchase all appliances/devices.

Table A.3
Intention to adopt smart home technologies. Table includes smart home technology items and percentage of respondents' intention to purchase.

Smart home technologies	Intend to purchase (%)	Do not intend to purchase (%)	Already Purchased (%)	Cannot be installed in current home (%)
Solar panels that generate electricity	19.7	36.1	11.6	32.6
Plug-in electric vehicle	20.7	56.8	4.1	18.4
Smart Thermostat (Nest, Ecobee, etc.)	26.6	43.7	13.9	15.8
Smart light bulbs (Philips Hue, etc.)	30.5	33.8	29.1	6.6
Smart Appliances (Samsung Family Hub refrigerator, Bosch Home Connect dishwasher, etc.)	28.5	47.8	10.9	12.8
Smart plug or power strip	30.5	37.8	25	6.7
Home Energy Monitoring Systems (HEMS) (Sense, CURB, etc.)	21.2	59.1	3.9	15.8
Home energy storage battery (Tesla Powerwall, etc.)	18.8	61.3	3.6	16.3

Table A.4
Binary logistic regression models predicting intention to purchase individual smart home technology items: solar system; electric vehicle; smart thermostat; and smart light.

	Solar system	Electric vehicle	Smart thermostat	Smart light
	Model D1	Model D2	Model D3	Model D4
	Odds ratio (p-value)	Odds ratio (p-value)	Odds ratio (p-value)	Odds ratio (p-value)
Respondent characteristics				
Female (vs. male)	0.412 (0.070)	0.765 (0.166)	0.790 (0.194)	0.962 (0.838)
Age (categories)	0.737*** (<0.001)	0.741*** (<0.001)	0.875 (0.079)	1.035 (0.669)
Bachelor's or higher (vs. less than bachelor's degree)	0.697*** (<0.001)	1.637* (0.020)	1.002 (0.992)	0.768 (0.230)
Household characteristics				
Household income	1.087* (0.013)	1.074* (0.023)	1.021 (0.487)	1.017 (0.589)
Single family home	1.173 (0.448)	0.754 (0.166)	1.188 (0.367)	0.936 (0.739)
Owner occupied household	1.436 (0.109)	1.020 (0.928)	1.224 (0.315)	0.760 (0.197)
Household size	1.080 (0.356)	0.965 (0.667)	0.926 (0.326)	0.947 (0.490)
Minors present (younger than 18 years old)	1.462 (0.134)	1.541 (0.080)	1.633* (0.035)	2.026** (0.005)
Midday occupancy change (weekdays) during SIP	0.920 (0.185)		1.024 (0.662)	1.076 (0.222)

(continued on next page)

Table A.4 (*continued*)

	Solar system	Electric vehicle	Smart thermostat	Smart light
	Model D1	Model D2	Model D3	Model D4
	Odds ratio (p-value)	Odds ratio (p-value)	Odds ratio (p-value)	Odds ratio (p-value)
Respondent characteristics				
		0.938 (0.273)		
Change in frequency of energy-related activities during SIP	1.011 (0.754)	1.030 0.377	1.154*** (<0.001)	1.157*** (<0.001)
Intercept	0.412 (0.070)	0.588 (0.262)	0.470 (0.101)	0.522 (0.174)
Akaike information criterion	669.97	733.12	782.35	699.42
N	662	712	641	522

Significance level: *p < 0.05; **p < 0.01; ***p < 0.001.

Table A.5
Binary logistic regression models predicting intention to purchase individual smart home technology items: smart appliance; smart plug; home energy monitoring system; and home battery storage

	Smart appliance	Smart plug	Home energy monitoring system	Home battery storage
	Model E1	Model E2	Model E3	Model E4
	Odds ratio (p-value)	Odds ratio (p-value)	Odds ratio (p-value)	Odds ratio (p-value)
Respondent characteristics				
Female (vs. male)	0.528*** (<0.001)	0.993 (0.968)	0.814 (0.195)	0.508** (0.001)
Age (categories)	0.818** (0.008)	1.065 (0.421)	0.779*** (<0.001)	0.770** (0.002)
Bachelor's or higher (vs. less than bachelor's degree)	0.942 (0.775)	0.602* (0.019)	0.858 (0.402)	1.366 (0.162)
Household characteristics				
Household income	1.028 (0.346)	1.040 (0.195)	1.018 (0.491)	1.016 (0.612)
Single family home	1.073 (0.714)	0.749 (0.131)	1.071 (0.686)	1.009 (0.967)
Owner occupied household	1.230 (0.311)	0.714 (0.102)	0.894 (0.542)	1.227 (0.363)
Household size	0.934 (0.374)	0.921 (0.290)	0.933 (0.325)	1.043 (0.606)
Minors present (younger than 18 years old)	2.136** (0.001)	1.283 (0.309)	0.693 (0.092)	1.346 (0.234)
Midday occupancy change (weekdays) during SIP	0.963 (0.493)	1.130* (0.042)	1.049 (0.355)	0.969 (0.597)
Change in frequency of energy-related activities during SIP	1.141*** (<0.001)	1.110** (0.001)	1.020 (0.469)	1.090* (0.015)
Intercept	0.794 (0.611)	0.584 (0.248)	5.512*** (<0.001)	0.455 (0.107)
Akaike information criterion	798.00	749.29	955.02	701.29
N	661	557	707	718

Significance level: *p < 0.05; **p < 0.01; ***p < 0.001.

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Endemic Water and Storm Trash to energy via in-situ processing

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ARTICLE INFO

Keywords:
Hurricane debris
Water hyacinth
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Waste-to-energy
Mobile processing

ABSTRACT

Significant capital is spent removing and disposing of biomass detritus produced by natural disasters and invasive species infestations. This presents an opportunity to turn the cleanup of these endemic wastes into cost-effective, sustainable bioenergy. Using hurricane debris and invasive water hyacinth as case studies, the results of the presented analysis show that carefully designed, relocatable biofuel facilities that produce energy from biowaste can be cost-competitive and carbon-negative compared to status quo baselines. Techno-economic and carbon accounting analyses show that bioenergy can be economical and sustainable over a range of debris scenarios and facility parameters. Transportation modeling shows that by integrating collection, volume reduction, and transportation, delivered feedstock costs can be reduced by 30–87% compared to status quo costs. For the case of hurricane debris, electricity from biomass boilers and pyrolysis generators with 70% capital utilization are competitive with diesel generators at 4 MW and 1.5 MW scales, respectively. For water hyacinth, anaerobic digestion paired with a harvester that gathers, crushes, and bags plants directly on the water could produce useful heat for a net profit of $9/GJ while offsetting 3 tons CO_2e per GJ. Ultimately, the present work shows that careful design and evaluation of bioenergy systems could enable an endemic Water and Storm Trash to Energy Via In situ Processing (WASTE VIP) system that reduces cleanup costs, increases energy security, and converts costly biomass waste into cleaner, cheaper energy.

1. Introduction

Bioenergy has significant potential to replace fossil energy and mitigate carbon emissions, but only if feedstocks are sustainably sourced and land-use change is carefully evaluated [1]. The large-scale production of energy crops can lead to intense land-use change, exemplified by the deforestation of the Amazon from sugarcane [2,3] and deforestation from oil palm production [4]. On the other hand, feedstock sources such as wood waste, animal manure, and municipal solid wastes are widely available [5]. In 2013, the United States generated 56 billion kilowatt-hours of energy from 187 million dry tons of such sources [6]. However, these wastes are byproducts that depend on the demand and the sustainability of conventional forest, agriculture, and municipal supply chains [1].

There exist biomass waste streams that are decoupled from existing supply chains, which we define as endemic biomass wastes. These include invasive plant growth, hurricane debris, and forest detritus from beetle infestations. These biomass sources are often created in high volumes and frequently result in economic losses and costly cleanup operations. For instance, India has an estimated 2 million hectares of aquatic weed coverage in the post-monsoon season [7], which could provide up to 540 million fresh tons of feedstock [8]. Hurricanes generated 1 million tons of debris in Puerto Rico in 2017 [9], 72 million tons in Florida in 2018 [10], and 700,000 tons in the Bahamas in 2019 [11]. The frequency and intensity of hurricanes are also expected to increase due to climate change [12], meaning increased debris expenses

Abbreviations: $, 2019 US Dollars (unless otherwise noted); AD, anaerobic digestion; BC, boiler combustor; BG, biogas; BTL, Biomass-to-Liquid; CAPEX, Capital Expenditure; CHP, combined heat and power; CO_2e, carbon dioxide equivalent emissions [kg or tons]; CY, cubic yards; DW, dry weight; DG, diesel generator; dmt, dry metric ton; EPA, Environmental Protection Agency; FEMA, Federal Emergency Management Agency (USA); FoRTS, Forest Residue Trucking Simulator; FW, fresh weight; GJ, gigajoule; hp, horsepower; IPCC, Intergovernmental Panel on Climate Change; LHV, lower heating value [MJ/kg or GJ/dmt]; MC, moisture content [%]; MJ, megajoule; MW, megawatt; MWe, megawatt; electricity-basis, MWh; megawatt-hour, O + M; Operations and Maintenance, PG; pyrolysis with generator, PMH; primary machine hour, SIF; Societal Impact Factor, TEA; Techno-Economic Analysis, USACE; United States Army Corps of Engineers, USVI; United States Virgin Islands, VS; volatile solids, WASTE VIP; Waste and Storm Trash to Energy Via In situ Processing, WH; water hyacinth, WS; wood stove, WtE; Waste-To-Energy, as in landfills.

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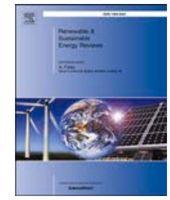

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and increased debris supply.

In the spirit of symbiotic systems [13], these endemic waste streams present an opportunity to turn expensive biomass cleanup efforts into bioenergy supply chains, providing low-cost feedstocks and additional economic incentives for still-maturing bioenergy and biofuel operations. The production of biofuels from wood and other waste sources is not yet established at scale; for example, Rentech canceled a commercial-scale biomass-to-jet fuel facility in 2013 due to high costs and low "near-term profitability" [14]. Dimitriou et al. (2018) found that biofuels produced from various Biomass-to-Liquid (BTL) facilities were 8–53% more expensive than gasoline and diesel [15].

Research has been conducted to enable feasible woody feedstock conversion through state-of-the-art conversion technologies such as hydrothermal liquefaction [16,17], which could greatly decrease capital and operational costs. However, feedstock costs can be 20–33% of production costs [15,18] and are likely to remain significant regardless of conversion technology. Key elements of the supply chain can greatly impact the delivered cost of a woody feedstock, for instance with distributed conversion [18,19] or distributed comminution [20]. Integration of feedstock machinery is also promising - Tsapekos et al. (2017) found that certain mowers could simultaneously harvest and pretreat meadow grass for anaerobic digestion, which decreased energy requirements and increased economic feasibility [21].

The present study broadens this integrated approach by proposing and evaluating mobile bioenergy systems that harvest, pretreat, and utilize feedstocks as close to the source as possible. Two recurring endemic biomass waste streams are considered: hurricane debris and invasive water hyacinth. These wastes are generated without regard to human input, and resources are continually allocated to collect, remove, and dispose of them. *In situ* processing in conjunction with already-existing supply chains (for hurricane debris) or mechanical harvesting requirements (for water hyacinth) could decrease handling costs and are the focus of this work.

The present study focuses on modeling the delivered costs of waste feedstocks and determining the economic costs and carbon impact of converting these feedstocks into bioenergy. Specifically, the objectives of this work are to determine the impact of mobile gathering and volume reduction on the delivered costs of terrestrial and aquatic crops over a range of transportation distances and moisture contents; and to evaluate the techno-economic and carbon accounting costs of converting those feedstocks into useful bioenergy. These generalized models provide specific guidance for the design of future machines, supply chains, and bioenergy facilities. While the present model focuses on technologically-mature bioenergy conversion pathways, the successful utilization of bio-debris will further the development of new supply chains and conversion technologies.

2. System backgrounds

2.1. Hurricane debris

Hurricanes generate debris which must be collected, delivered to a central site, shredded, and disposed of. These operations are costly: in North Carolina in 2018, debris removed from public streets and delivered to temporary sites was reimbursed for $37-$54 per ton at transportation distances under 5 miles [22], and $576 million was allocated for debris cleanup in Puerto Rico after Hurricane Maria [23].

Furthermore, many hurricane-prone islands have limited landfill space, exacerbating post-disaster debris management issues. In the U.S. Virgin Islands (USVI), the two operating landfills are near capacity with no viable options for a new one. After Hurricanes Irma and Maria, the USVI government approved the use of incinerators for debris disposal [24]; however, the proposal was vetoed due to air quality concerns, and instead the debris was exported on barges at significant cost [25]. Disasters also create power disruptions and fuel shortages. After Hurricane Maria, the damaged port and transportation infrastructure in Puerto Rico caused major fuel shortages, which exacerbated the lack of access to electricity as households and hospitals turned to diesel generators. A week after the hurricane, 58 of 69 hospitals had no access to fuel or electricity [26].

This presents an opportunity for an integrated biowaste-to-energy system such as a barge-mounted bioenergy plant, which follows hurricanes and docks at ports to process debris. The barge-mounted plant would integrate into existing debris cleanup operations, divert waste from overfilled landfills, produce valuable electricity or biofuels, and turn federal aid spent every year on debris cleanup into a useful energy supply.

While major hurricanes have generated significant debris in the last few years, supplies are not certain or predictable. The present work thus builds a delivered cost model that is generalized across a range of transportation distances and moisture contents and presents results for varying facility scales and utilizations to quantify the impact of feedstock shortages.

2.1.1. Feedstock composition and conversion

The composition of the debris affects the technical and economic feasibility of different bioenergy conversion pathways. FEMA estimates that 30% of hurricane debris is "clean woody debris", with the remaining 70% containing other combustibles, soil, metals, and landfill materials which require sorting [27]. After Hurricane Katrina, temporary collection sites in several counties were dedicated exclusively to vegetative debris, and chips generated from grinding operations were used for mulch or boiler fuel - saving the USACE over $600,000 in landfill fees in a single county. Vegetative debris that cannot be recycled is typically burned or landfilled [28].

There is limited data on the specific composition of woody hurricane debris. The vegetative debris is composed mostly of tree branches [27], while whole trees and stumps are typically removed under separate contracts [28]. Only the smaller-sized vegetative debris is considered in the present work, and the composition of forest harvesting residues is used as a proxy. Reported ash content for harvest residues ranges from 0.4 to 0.69% [29] to 1–2% [19,30]. The ash content of hurricane debris would most likely vary with local vegetation; however, even commercial bioenergy plants with dedicated feedstocks see wide variability in ash content throughout the year [31]. The moisture content (MC) in fresh green wood can range from 40 to 70% and is typically higher in wet environments [32]. The present model uses a base value of 50% MC, consistent with average values used in Ref. [19,33,34], and the sensitivity of results to MC is discussed.

Forest residues can be converted into several useful products, such as into transportation fuels via gasification or pyrolysis with further upgrading [35]. Such technologies have been proven in demonstration-scale units: in 2016, the Northwest Advanced Renewables Alliance (NARA) produced 1050 gallons of jet fuel from forest slash and pulp mill reject material [36], and Kim et al. (2016) produced bio-diesel from wood chips in a 1 barrel-per-day unit [37]. However, the feasibility of commercial wood-to-biofuel facilities is still uncertain. While wood wastes may contribute to the profitability of biofuel facilities, such as in the Red Rock facility scheduled to open in Spring 2020 [38], uncertainties in feedstock composition and availability favor more flexible and technologically mature pathways such as boiler combustion and pyrolysis.

In boilers, wood is combusted to generate electricity and heat. Such systems are widely deployed, particularly as Combined Heat and Power (CHP) systems, and they can range from distributed 50 kW to utility scales [35,39]. In pyrolysis, wood is heated to high temperatures in the absence of oxygen to produce bio-oil, biochar, and syngas. The ratio of the final products and their respective compositions depends on the reaction temperature, residence time, and feedstock quality [39]. Bio-oils of sufficient quality can be upgraded into drop-in transportation fuels [40] or be used on the spot for electricity generation [41]. Pyrolysis is a mature technology, evidenced by the existence of commercial mobile units [41,42] and consideration in literature for converting forest residues [19,30,43].

2.2. Invasive water hyacinth

Water hyacinth (*Eichhornia crassipes*) is a freshwater aquatic plant that has been called the world's worst water weed, having infested waterways in the Southern US, Africa, China, and India [44]. Water hyacinth forms thick, floating mats, which crowd out other life and cause severe economic and ecological problems. The invasion of water hyacinth to Dianchi Lake in China caused 60% of the local species to die out [45]. On Lake Victoria, water hyacinth reduced the ability to fish by 45% [46]. Additionally, as large plant mats die off in the winter or get sprayed with herbicides, they deplete oxygen and deteriorate water quality [44].

Due to these significant detrimental impacts, water hyacinth control has incurred high costs around the world. Louisiana spent $124 million from 1975 to 2013 suppressing hyacinth growth, resulting in a net economic benefit of $4.2 billion to the various fishing, hunting, boating, and water-dependent businesses [47]. Lu et al. (2007) reported that in China, water hyacinth control cost $12 million annually, yet the plant caused $1 billion in economic loss in a given year [48].

Lake Tana, Ethiopia's largest lake and the source of the Blue Nile, is essential to the region's economy and ecology; however, water hyacinth coverage doubled within two years from 2011 and is now estimated to cover 40,000–50,000 ha [49]. Its tremendous growth, equivalent to 8–10 million tons, is in part due to untreated wastewater dumped in the lake; allowing the water hyacinth to grow and decompose contributes to ecosystem deterioration. An aquatic plant harvester was donated to Lake Tana to aid the cleanup effort, but the removal process has been hindered by breakdowns and maintenance delays [50].

2.2.1. Feedstock location, composition, and conversion

Water hyacinth has physical attributes that make it an ideal bioenergy feedstock - it grows rapidly, does not compete with crops for land, and has a low lignin content [51]. The rapid growth of water hyacinth in polluted areas is a natural response to excessive nutrient runoff, as water hyacinth has been grown explicitly for water quality improvement and remediation for decades [52,53].

Anaerobic digestion was selected to convert water hyacinth to useful bioenergy due to its technological maturity, applicability in the developing world, and ability to readily convert wet feedstock. The biogas potential of water hyacinth can depend on the particle size, inoculum source, feeding rate, and retention time. Biogas produced from water hyacinth is approximately 60–67% methane [54,55]. Priya et al. (2018) operated an anaerobic digester fed with fresh, crushed water hyacinth for one year, with yields of approximately 5.8 L methane per kgFW at 12 day residence times [54]. Others report methane yields of 5.6–13 L/kgFW at 8–30 day residence times [55,56]. The present model assumes a base digester productivity of 6 L methane per kilogram water hyacinth and assumes that the biogas is used for cooking stoves while the remaining slurry is sold as fertilizer.

The rapid spread of water hyacinth requires new solutions for a rapidly deployable and sustainable cleanup operation. There are significant transportation challenges with using water hyacinth, as the bulk density is reported to be 100–300 kg/m^3 with 90–95% being water by weight [57]. The present work proposes and evaluates the effect of on-water volume reduction and in-water bagging for plant towing and later digestion. A towing transportation model is created to evaluate the delivered costs of the status quo and proposed improvements. A techno-economic and carbon accounting model are then used to evaluate the economic and carbon costs associated with the production of biogas from anaerobic digestion of water hyacinth.

3. Accounting methodology

A two-step model is used to evaluate the proposed feedstock supply and its energy conversion potential (Fig. 1): first, the delivered costs including the collection, volume reduction, and transportation to a bioenergy facility are modeled and results including sensitivities to distance are presented. Second, the delivered costs are used to evaluate the energy production cost and specific emissions of the bioenergy pathways compared to status quo baselines.

3.1. Delivered cost

The delivered cost of the biomass is the cost of harvesting, transporting, comminuting, and handling the feedstock before it gets delivered to the bioenergy facility [58].

The delivered cost of the biomass is modeled as a function of the loading cost (C_{load}), chipping cost (C_{chip}), sorting cost (C_{sort}), transportation cost ($C_{transport}$), and offset tipping fee (C_{tip}):

$$C_{del} = C_{load} + C_{chip} + C_{sort} + C_{transport} - C_{tip} \tag{1}$$

In existing debris management scenarios, biomass is already 'delivered' to landfills and incurs harvesting, transportation, and comminution costs. These costs are still modeled and included, and potential revenues or offsets from replacing existing operations are discussed.

3.1.1. Labor costs

Labor is a major component of operational cost, and wages can vary widely from region to region. A labor cost of $50 per hour is used for the conversion of hurricane debris, which is assumed to cover technical operators and is consistent with literature sources using similar technologies [19,43]. A labor cost of $2 per hour is used for the conversion of water hyacinth, which is higher than wages reported in the cleanup of WH in Ethiopia [50] but more globally-applicable in a developing world scenario.

3.1.2. Machinery costs

The present model primarily uses equipment and equipment rates suggested by FEMA [27,59] and supplemented by equipment specifications used in the Forest Residues Transportation Costing Model [60]. A truck-mounted knuckleboom loader is used for loading into trucks and a tractor-mounted knuckleboom loader is used for loading into chippers [27,59]. The debris is transported using trucks with a roll-off container - standard in debris collection operations [27] - with an additional pulled pup trailer, and 100 CY and 21-ton payload capacity [60].

A variety of comminution equipment can be used, including chippers, horizontal grinders, tub grinders, and shredders [60,61]. Though grinders are frequently used in literature to grind feedstocks down to 3mm levels for biofuel production [19,43,62], data reviewed by Bergstrom et al. (2019) showed significant energy efficiency advantages in using chippers instead of grinders [61]. The present model assumes the use of the HG6000 chipper, which is used in hurricane chipping operations [59,63] and can be equipped to produce chips down to 3.2 mm [64].

Conversion technologies that require smaller chip sizes incur higher chipping energy costs. The present model assumes that combustion requires 50 mm chips and an additional 108 MJ/m^3, and pyrolysis requires 3 mm chips and an additional 180 MJ/m^3 [61]. The chipper throughput is assumed to be 26 tons/PMH with no dependence on moisture content, as observed by Bergstrom et al. (2019) [61] - this throughput is 4–5 times lower than default values used by others [33,62,65] but is assumed to reflect a practical scenario. The present model also assumes static sorting costs of $1.76/dmt [66]. The density of unchipped debris and chipped debris is assumed to be 118 kg/m^3 [27] and 236 kg/m^3 [67] respectively.

Chipping and transportation processes are paired with loaders (for

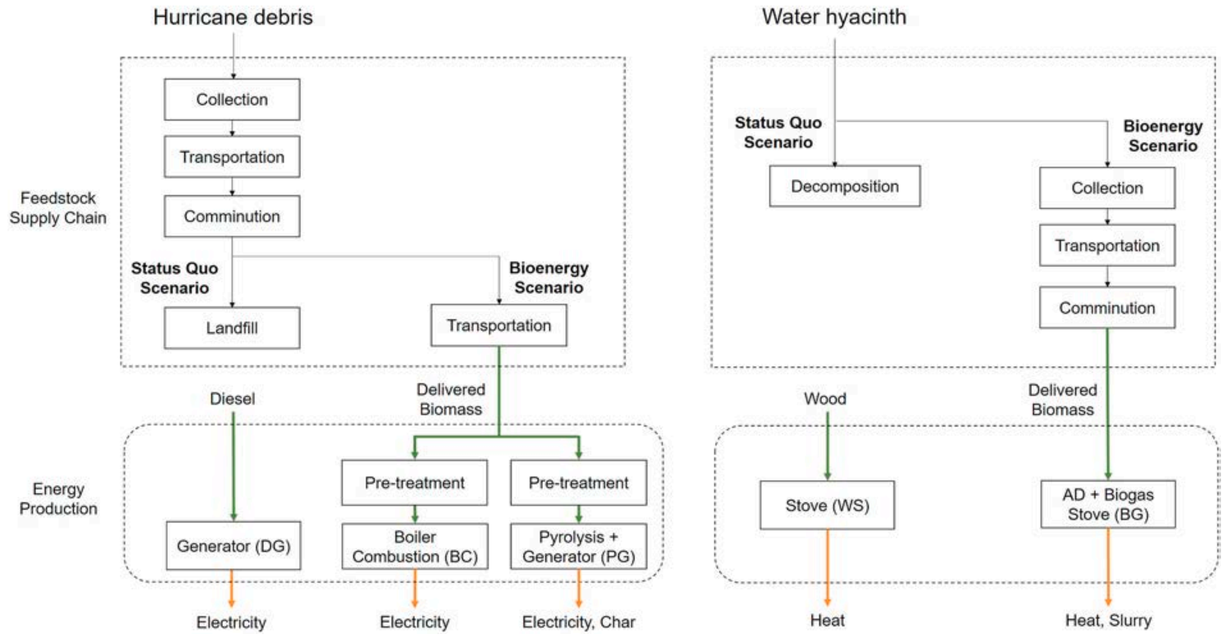

Fig. 1. Components used to evaluate the delivered cost of feedstock supplies and the resulting energy production costs. Left: hurricane debris. Right: invasive water hyacinth.

instance, with truck-mounted knuckleboom loaders), and the throughput of each step ($throughput_n$) can be expressed as

$$throughput_n = \min\left(throughput_i \cdot \eta_i, throughput_j \cdot \eta_j\right) \quad (2)$$

where η is the utilization efficiency and i, j denote the equipment required in that step. Mobile equipment is assumed to be utilized less efficiently than terminal equipment; Belbo et al. (2014) used utilization efficiencies of 74% for a roadside chipper, and 90% for a terminal chipper [20]. In practice, chipper utilization can be closer to 40%, due to trucking delays [68] or low trucking productivity [66]. Because the base chipper productivity assumed from Bergstrom et al. (2019) [61] is conservative compared to those measured from logging operations [66, 68], our model assumes a roadside chipper utilization of 60%. The base loader utilization is assumed to be 80% [60], however, the loader is almost always constrained by the chipper throughput.

The specific cost of a given step is then calculated as

$$C_n = \frac{rate + W}{throughput_n} \cdot (1 + MC) \quad (3)$$

where C_n is the specific cost [$/dmt], *rate* is the hourly equipment rate [$/PMH], W is the labor wage [$/hr], $throughput_n$ is the fresh weight throughput [tons/hr], and MC is the moisture content.

The primary machine rates taken from FEMA's Schedule of Equipment Rates (2019) include depreciation, maintenance, overhead, fuel, and all other operating costs other than labor [59]. Model parameters are summarized in Table 1.

3.1.3. *Transportation costs*

The total transportation cost can be expressed as a sum of the fuel costs, C_{fuel}; wage-based driving costs, C_{rate}; and the handling cost, $C_{handling}$:

$$C_{transport}(l, N) = C_{fuel}(l) + C_{rate}(l) + C_{handling}(N) \quad (4)$$

and is a function of distance traveled (l) and the number of trips (N). This cost is generalizable whether the stated vessel is a truck or a boat.

The fuel cost C_{fuel} [$] is given by

$$C_{fuel} = f_a C_{diesel} l \quad (5)$$

where f_a is the fuel consumption [L/km], C_{diesel} is the cost of diesel [$/L], and l is the distance traveled [km]. Truck fuel efficiency is assumed to be 0.47 L/km [60] and diesel is assumed to cost $0.72/L.

The distance-variable transportation cost, C_{rate} [$] is calculated as:

$$C_{rate} = \frac{rate + W}{v} \cdot l \quad (6)$$

where *rate* is the hourly machine rate [$/PMH], W is the hourly wage [$/hr], v is the travel speed [km/hr], and l is the distance traveled [km].

Finally, the trip-variable handling cost $C_{handling}$ [$] can be expressed as:

$$C_{handling} = N t_{handling} W \quad (7)$$

where N is the number of trips and $t_{handling}$ is the load/unload time [hr/

Table 1
Assumed values for the machinery used in the delivered cost analysis.

	Mobile Loader	Stationary Loader	Mobile Chipper	Stationary Chipper	Aquatic Harvester
Machine	Truck-mounted knuckleboom	Tractor-mounted knuckleboom	Vermeer HG6000[a]	Vermeer HG6000	Aquamarine H5-200[b]
Machine rate ($/PMH)	$53.22	$169.74	$59.12	$59.12	$4.58
Base Throughput (tons/hr)	60	132.36	26	26	
Horsepower (hp)	173	173	630	630	24.8
Utilization (%)	80%	80%	60%	100%	25%
Fuel consumption (L/hr)	14.4	14.4	118.4	118.4	
Source	[59,60]	[59,60,66]	[59,61]	[59,61]	[75,137]

[a] Observed chipper throughputs reported by Ref. [61] are used, which are significantly lower than throughputs reported by others. Hence, 100% utilization is used for the stationary scenario.
[b] Base cost of $68,509 as reported by Ref. [137] with 3% interest rate, 5% O+M, and 15-year lifetime.

trip].

The number of trips and the handling time are functions of the carrying capacity of each truck or vessel. The actual carried load, L_a, depends on the density of the plant, ρ_p, and the carrying capacities V_{cap} [m^3] and m_{cap} [kg]:

$$L_a = \min(\rho_p V_{cap}, m_{cap}) \tag{8}$$

And the total number of trips and handling time can be expressed as

$$N = \frac{m}{L_a} \tag{9}$$

$$t_{handling} = \frac{L_a}{r_{load} + r_{unload}} + t_{delay} \tag{10}$$

where m is the total amount of debris [tons], r_{load} and r_{unload} are the rates of loading and unloading [tons/hr], and t_{delay} is the waiting time per load (assumed to be 20 min).

Importantly, the total distance traveled, l, is also a function of the total number of trips:

$$l = 2Nd \tag{11}$$

where d is the one-way transportation distance [km].

The sensitivity of cost to travel distance and increased carrying capacity (via mobile chipping) is discussed in results.

3.1.4. Aquatic plant transportation methods

This work evaluates three aquatic plant transportation scenarios:

1 Transport plants on deck with no volume reduction (deck volume restriction)
2 Transport plants on deck with volume reduction (deck mass restriction)
3 Tow plants in a bag (tow capacity restriction)

To evaluate the specific energy and cost required for these methods, a base transportation distance of 100-m is used. The transportation energy is proportional to the drag force, F_D:

$$F_D = \frac{1}{2}\rho v^2 A C_d \tag{12}$$

where F_D is the drag force [N], ρ is the water density [kg/m^3], v is the relative velocity of the fluid [m/s], A is the wetted surface area [m^2], and C_d is the experimentally-determined coefficient of drag.

The fuel consumption of an aquatic harvester can then be calculated as

$$f_a = \frac{F_D E_f}{\eta_{prop}} \tag{13}$$

where f_a is the fuel consumption [L/km], E_f is the fuel energy density [L/J], and η_{prop} is the propeller efficiency. Equations (4)–(11) can then be adapted entirely for aquatic plant transportation, with specific parameters summarized in Table 2.

3.1.4.1. Towing on a boat - volume or mass restriction

The drag on an aquatic harvester is estimated using the correlation [69]:

$$C_D = \frac{0.075}{(\log Re - 2)^2} \tag{14}$$

and was found to be $C_D = 0.014$ for a standard 5.8m-long harvester. The area of interest is the wetted area of the harvester hull.

3.1.4.2. Towing in a bag

The water hyacinth can also be towed in a bag or in the anaerobic digester itself. Typical smooth-surface long cylinder drag coefficients are between 0.87 and 0.99 depending on length-to-diameter ratios; a length-to-diameter ratio of 7 (or above) and a resulting drag coefficient of $C_D = 0.99$ is assumed [70]. In this scenario, pressure drag dominates and the area of interest is the frontal area, $A = \pi R^2$, with an assumed bag radius of $R = 0.5m$.

The bag pack increases the 'carrying' capacity of the harvester to its towing capacity; however, a harvester is still required to tow the bags and the drag of a harvester is included in the bag-pack scenario.

Table 2
Key parameters used in the delivered cost model, techno-economic model, and carbon accounting for water hyacinth.

Parameter	Value	Source
Labor cost ($/hr)	$2	
Open decomposition emissions (kg CO2e/dmt)	5442	[71]
Water Hyacinth Physical Properties		
Volumetric density (kg/m^3)	167	[72]
Areal density (kg/m^2)	20	[8]
Dry matter content (%)	7%	[54]
Growth rate (kg/m^2/day)	0.2	[73]
Lower Heating Value (MJ/kg)	14.58	[74]
Harvest and Transportation Parameters		
Boat power (hp)	24.8	[75]
Estimated bollard tow (N)	1103	[76]
Propulsion efficiency (%)	24%	[77]
Travel velocity (m/s)	0.4	
Harvester length (m)	5.8	[75]
Harvester width (m)	2.3	[75]
Harvester draft, loaded (m)	0.39	[75]
Harvester drag, C_D	0.014	[69]
Bag length-to-diameter Ratio	7	
Bag drag, C_D	0.99	[70]
Bag radius (m)	0.5	
Energy Production Parameters		
Specific methane generation (L/kgFW)	6	[54]
Pre-Digester Volume Reduction (%)	70	
Fertilizer profit ($/dmt)	$40.86	[71]

3.2. Techno-economic analysis

The goal of the techno-economic analysis is to determine the energy production cost, which is a function of the delivered feedstock cost and the costs associated with operating the conversion equipment. The production cost [$/GJ] is given by Ref. [15]:

$$\dot{C}_{GJ} = \dot{C}_{del} + \dot{C}_{process} + \dot{C}_{CAP} - \dot{C}_{credit} \tag{15}$$

where $\dot{C}_{del}$ is the delivered cost, $\dot{C}_{process}$ is the processing cost, $\dot{C}_{CAP}$ is the capital and O + M cost, and C_{credit} is the value of any co-product credits. The economic value of co-products is credited towards the overall production cost as described in Section 3.2.4.

In general, costs are converted from per-dmt costs (C_{dmt}) to per-GJ costs ($\dot{C}_{GJ}$) with the equation

$$\dot{C}_{GJ} = \frac{C_{dmt}}{E_{out}} \tag{16}$$

where E_{out} is the overall feedstock-to-energy conversion [GJ/dmt].

3.2.1. Process yields and energy requirements

The processing cost is the sum of the additional drying and conversion energy costs [$/GJ]:

$$\dot{C}_{process} = \dot{C}_{dry} + \dot{C}_{conv} \tag{17}$$

and each conversion method has different yields, required moisture contents, and process energy requirements.

Excess moisture must be evaporated prior to useful conversion. The required drying energy can be expressed in terms of target MC change as

$$\dot{E}_{dry} = \frac{(\Delta MC)L_w}{\varepsilon_{dryer}} \quad (18)$$

where $\dot{E}_{dry}$ is the specific drying energy [MJ/kgDW], ΔMC is the target change in moisture content, L_w is the latent heat of evaporation of water (2.26 MJ/kg), and ε_{dryer} is the dryer efficiency (assumed to be 0.5) [19]. The biomass feedstock could be dried by up to 20% using waste heat [67] or even dried partially en route using transportation exhaust [78]; however, the present model assumes that all excess moisture must be removed.

Reported electrical efficiencies for boiler combustion range from 16 to 34%, while total thermal efficiencies range from 51 to 95% [34,62,79]. This analysis assumes biomass is combusted with 16% electrical efficiency at 50% target feedstock MC [34]. While 30–60% of the combusted energy exits as heat, this study assumes that heat markets in hurricane-prone regions are limited and that heat is wasted.

For pyrolysis, this study assumes a target moisture content of 10% and resulting pyrolysis yields from Brown et al. (2013) [19], which produce primarily bio-oil from forest residues: 57% bio-oil, 26% bio-char, 15% syngas, and 2% ash by mass (51%, 42%, 7%, and 0% respectively by energy). These yields are similar to those found by Carrasco et al. (2017) [80], whose process yields deliberately produce enough char to replace the need for external fossil energy. Specifically, enough char is generated and combusted to fully meet the energy requirements of the pyrolysis reaction. This study thus assumes that char combustion supplies the 348 MJ/dmt required for the pyrolysis process [19]. Although feedstock could likely also be dried using waste process heat [67] or using combusted syngas [19,81], this analysis assumes that feedstock drying energy is supplied by diesel generators. The bio-oil is combusted in a diesel generator [82,83] to produce electricity at 40% efficiency.

The present model assumes that the anaerobic digestion of water hyacinth yields 6 L methane per kgFW water hyacinth, or 3.12 GJ per dmt. The remaining organic material decomposes into fertilizer slurry at a rate of 0.038 tons slurry per fresh ton of water hyacinth [71]. The economic value of digestate slurry and other byproducts are discussed in Section 3.2.4. Other fuel parameters are presented in Table 3 and a summary of the energy balance for each scenario is given in Figs. 2 and 3.

3.2.2. Capital costs

The capital and O + M production cost, $\dot{C}_{CAP}$ [$/GJ], is given by Ref. [15]:

$$\dot{C}_{CAP} = \frac{ACC + TOMC}{EO \cdot OH} \quad (19)$$

where ACC is the annualized capital cost [$], $TOMC$ is the annual Operation and Maintenance (O + M) cost [$], EO is the theoretical energy output [GJ/hr], and OH is the facility's annual operating hours. The annual operating hours can also be expressed as a utilization factor or a capacity factor, and baseline utilization is presented for each technology in Table 4.

Table 3
Fuel parameters used in the presented models.

Parameter	Value	Source
Diesel cost ($/L)	0.72	
Diesel energy density (MJ/L)	35.7	
Diesel and bio-oil combustion efficiency (%)	40	
Wood waste LHV (MJ/kgDW)	18	[19]
Fuelwood (gathered) LHV (MJ/kgDW)	16	[84]
Fuelwood stove efficiency (%)	20	[85]
Methane energy density (MJ/m^3)	36.4	
Biogas stove efficiency (%)	55	[86]
Biogas methane percentage (%)	65	[54,71]

The annualized capital cost, ACC, is calculated as [15].

$$ACC = C \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \quad (20)$$

where C is the upfront capital investment [$], r is the interest rate, and n is the lifetime of the equipment. A summary of assumed capital costs, interest rates, lifetime, and base utilization is given in Table 4.

To accurately transfer literature-reported and commercially-reported costs, a scaling factor was applied to reported capital costs:

$$\frac{C_1}{C_2} = \left(\frac{S_1}{S_2}\right)^p \quad (21)$$

where C_1 and C_2 are the reported capital costs [$], S_1 and S_2 are their respective scales (MW for power plants), and p is the scaling exponent, with $p < 1$ representing typical economies of scale. Scale factors for various biomass facilities range from 0.65 to 0.9 [15,91–93]. The present model assumes $p = 0.8$, which is conservative; however, in post-disaster scenarios larger equipment may incur higher costs than in standard utility-scale scenarios.

The capital costs for biomass combustion are modeled using overnight generator costs provided by the U.S. EIA (2020), at $4104/kW for a 30MWe scale [87]. The scaled costs range from $5112-$9308 for 0.5–10MWe facilities, in line with those provided by other sources [35,94]. The 50 ton-per-day mobile pyrolysis unit modeled by Brown et al. (2013) [19] is used because they evaluate a transportable facility that runs off forest residues, and they specifically report capital, maintenance, and labor costs. The capital cost for a flexible polyethylene anaerobic digester was assumed to be $1300 for a 40 m^3 system [Personal Communication (2020)] with a 15-year lifetime [95].

3.2.3. Operation and maintenance costs

The operation and maintenance costs of a facility typically include labor, maintenance, utilities, and raw materials, and these costs vary by conversion technology and scenario. The annual O + M cost is commonly expressed as a fixed percentage of capital costs [15]. O + M costs for biomass combustion are around 3–4.5% of the total capital cost [87,96] and for backup diesel generators around 4.4% [89]. Dimitriou et al. (2018) report fixed O + M costs of 4% for large-scale BTL facilities [15], whereas Sorenson (2010) report costs of 9–11% for a mobile pyrolysis facility [88]. Reported insurance costs range from 1 to 3% [15,88,96]. The present model uses insurance-inclusive O + M costs of 5.5%, 5%, 10%, and 2% for combustion, diesel generators, pyrolysis, and anaerobic digester facilities respectively.

3.2.4. Co-product economic credits and offset landfill fees

Conversion processes can generate valuable products in addition to energy. Biochar is produced from pyrolysis, which can be used for combustion, for soil remediation, or as activated carbon [97]. Campbell et al. (2018) found reported biochar prices to range from $80-$13,000 per ton [98], and industry surveys report biochar prices between $600-$1600/ton [99]. However, due to local market uncertainty, the present study assumes that biochar is a byproduct with no additional revenues or costs. The actual value of the produced biochar, which depends on feedstock quality, contaminants, volatile matter, and ash content [98], is left for future work.

The slurry produced from anaerobic digestion could be sold as bio-fertilizer, although literature sources report varying fertilizer prices between -$4.14 and $21 per ton of biomass input [71,90,100]. In practice, the composition and the value of digester slurry depend on the growing environment of the water hyacinth. Contaminants from heavy metal-laden or heavily polluted water could be absorbed by the plants and produce metal and nutrient-dense slurry [101]; the heavy metals could be extracted and become a further value stream using adsorbent polymers, as in the target adsorption of metals from seawater [102]. Fertilizer revenues from Wang et al. (2012) [71] were used in the

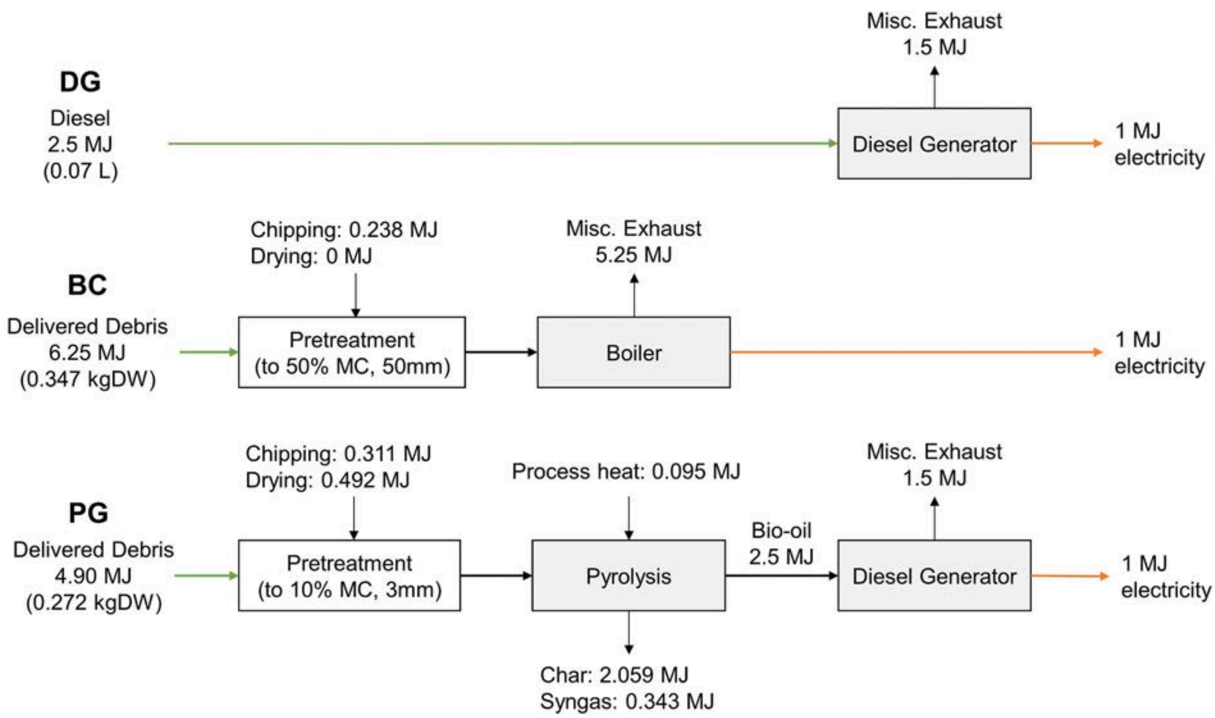

Fig. 2. Energy balance of the diesel generator (DG) baseline, boiler combustion (BC), and pyrolysis generator (PG) scenarios for the utilization of hurricane debris. Moisture content of hurricane debris is assumed to be 50%.

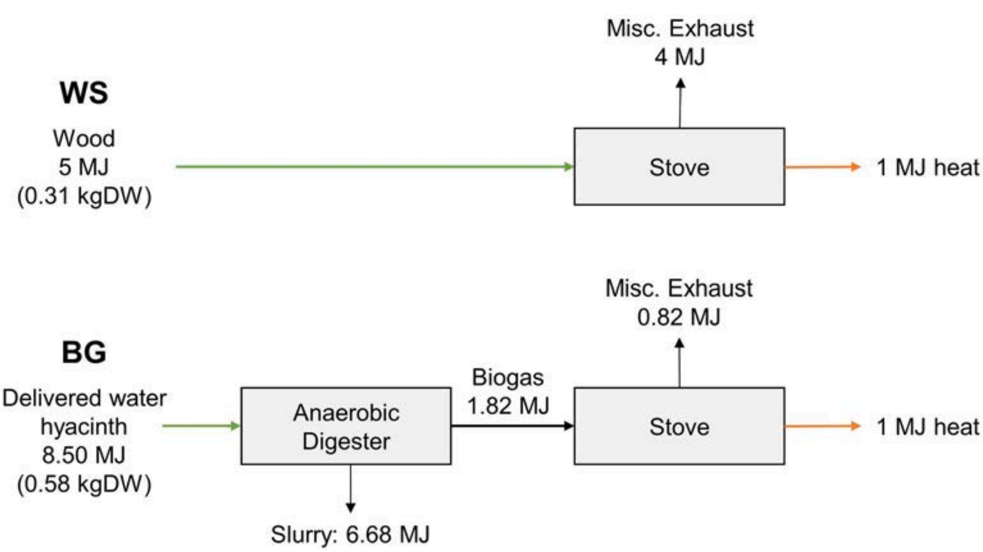

Fig. 3. Energy balance of the wood stove (WS) baseline and biogas (BG) scenarios for the utilization of invasive water hyacinth.

present model for the anaerobic digestion of water hyacinth, whose resulting slurry could have different compositions than more traditional sources.

The proposed bioenergy scenario also diverts debris from landfills, which typically incurs a tipping fee between $35-$68 in the United States [103]. Post-hurricane tipping fees may be closer to $20/ton ($4/m^3 from Ref. [28]), which is the value used in the present work. In lower-income countries, the World Bank estimates per-ton waste costs of $10–20 for landfilling and $2–8 for open dumping; however, these fees are not always charged or recuperated [104] so a $0 tipping fee is assumed for the utilization of water hyacinth.

3.3. *Carbon accounting*

The goal of the carbon accounting is to compare bioenergy systems converting endemic wastes to existing energy generation systems. The functional unit is thus “1 MJ of useful energy produced”. The carbon accounting evaluates the 100-year Global Warming Potential (GWP_{100}) of each scenario, accounting for greenhouse gas emissions from three major sources: combustion emissions, process fuel emissions, and offset decomposition of biomass. GWP_{100} factors of 28 and 265 are used for methane and nitrous oxide respectively [105]. Carbon offsets associated with biomass decomposition are credited to the bioenergy systems (system expansion), as discussed in Section 3.3.3.

Table 4
Capital equipment and energy conversion parameters used to model energy production costs.

	Biomass Boiler	Pyrolysis	Diesel Generator	Anaerobic Digester
Base Cost	$4012/kWe	$1917/kWe	$800/kWe	$1300
Base Capacity	30 MW	5.3 MW (fuel basis)	500 kW	40 m^3
Scale Factor	0.8	0.8	0.8	
O + M (% of Capital Cost)	5.5%	5%	10%	2%
Interest rate (%)	7%	7%	7%	3%
Plant lifetime (yrs)	30	20	10	15
Base utilization (%)	50%	90%	50%	95%
Base efficiency (%)	16%	51% wood to bio-oil, 40% bio-oil to electricity	40%	55% (stove heat)
Sources	[34,87]	[19,82,88]	[89]	[90], Personal Communication (2020)

3.3.1. Combustion emissions

The present model uses default combustion emissions provided by IPCC (2006) [106] (Table 5). The emissions on a useful-energy basis are a function of the fuel-to-energy conversion efficiency.

Importantly, biogenic and fossil CO_2 contribute differently to the carbon cycle, as fossil carbon necessarily increases atmospheric carbon concentrations whereas biogenic carbon does not necessarily do so [107]. Because the combustion of biomass emits carbon that was sequestered on shorter time scales (i.e. in the last 100 years), the life-cycle impact of biogenic emissions is often assumed to be zero [34,108,109]. However, the biomass wastes in this study are created by 'natural' sources and their cleanup (or lack thereof) is a conscious decision with potentially significant impacts on ecosystems and surrounding land - for instance, allowing hurricane debris to remain and decompose can suppress forest productivity and nitrogen availability by over 40% [110]. This study includes biogenic carbon emissions in order to fully assess the environmental impact of the bioenergy scenarios, but biogenic emissions are labeled separately to differentiate them from fossil or methane emissions.

3.3.2. Process emissions

Each stage of the debris supply chain requires fuel energy. The present model assumes that additional chipping and drying requirements burn diesel fuel with 35.7 MJ/L density at 40% efficiency. For pyrolysis, process heat is supplied by the combustion of char, which emits biogenic carbon.

3.3.3. Co-product carbon credits and offset decomposition

The carbon impacts of digestate slurry and pyrolysis biochar are assumed to be zero due to uncertainties in market value and expected utilization, as discussed in section 3.2.4. However, the proposed bioenergy systems also replace and offset the natural decomposition of biomass wastes in open air and landfills. When biomass openly decomposes, a fraction of the original carbon content converts into carbon dioxide and methane. The IPCC (2006) estimates the methane generation potential of waste decomposition as [111]:

$$L_o = W \cdot DOC \cdot DOC_f \cdot MCF \cdot F \cdot 16/12 \quad (22)$$

where L_o is the methane generation potential [kg CH_4], W is the mass of the deposited waste [kg], DOC is the degradable organic carbon fraction, DOC_f is the decomposable fraction of the DOC, MCF is the methane correction factor, and F is the methane fraction of the generated landfill gas. The non-methane fraction of landfill gas is assumed to be carbon dioxide.

Default values from IPCC (2006) [106] for the decomposition of wood ($DOC = 0.42$, $DOC_f = 0.5$, $MCF = 0.6$, $F = 0.5$) result in 2583 $kgCO_2e$ per dmt of hurricane debris. Water hyacinth decomposes more readily than wood (higher DOC, DOC_f on a dry basis) and produces a higher methane fraction; values from Wang et al. (2012) [71] for the decomposition of water hyacinth result in 5442 $kgCO_2e$ per dmt.

Table 5
Combustion emission factors on the basis of fuel lower heating value [106].

Fuel source	Emission Factor (kgCO2e/TJ)
Stationary diesel	74,343
Mobile diesel	75,243
Wood/wood waste	113,900
Bio-char ("Other solid biomass")	101,900
Biogas	54,655

4. Results and discussion

4.1. Hurricane debris

4.1.1. Delivered cost results

This study takes a generalized approach to transportation distances and moisture contents in order to inform a range of future debris scenarios. Results show that mobile chipping is 30% cheaper even at 30-km distances and would expand the range of useable and economically viable feedstocks (Fig. 4). Despite lowered rates of chipper and loader utilization, mobile chipping increases feedstock density and increases the payload from 9 to 18 tons per truckload. Mobile chippers could be integral for proposed systems which run off uncertain feedstock supplies - for instance, a bioenergy operation with a target feedstock cost of $50/ton could transport pre-chipped waste as far as 90 km as opposed to only 45 km if the debris were trucked 'as is'. In general, modeled delivered costs are on par with those of other studies [112,113]; however, it is evident that exact supply chain configurations have a significant impact on results.

The delivered costs in Fig. 4 do not include potential revenues or reimbursements from replacing existing debris fees: in North Carolina in 2018, reimbursements were $37–54/ton for debris collection and hauling, $9–50/ton for landfilling, and $10–19/ton for chipping/reduction [22]. Debris incineration costs $45/ton [114,115]. In practice, the proposed systems could operate with debris contractors or operate akin to Waste-to-Energy (WtE) landfills, which still charge tipping fees; however, there is unknown precedent of such an operation for debris cleanup. One precedent may be the production of mulch from hurricane debris, although the mulch is often given away for free [116] and without reimbursement [28].

4.1.2. Techno-economic analysis results

The delivered costs for the bioenergy facilities are modeled at 80-km transportation distance, 50% MC, and $20/ton offset tipping fee. The resulting energy production cost is dominated by the capital cost of the conversion equipment (Fig. 5b), and as a result biomass operations are very sensitive to scale and utilization rate (Fig. 5a). For 5MWe (around 25,000 dmt/year) facilities at 50% utilization, capital and O + M costs are 65% and 46% of total production costs for BC and PG facilities respectively.

The results show that a 4 MWe boiler facility with 70% utilization and converting 31,000 dmt/year is competitive with diesel electricity production; a boiler facility with 50% capital utilization would need to convert 107,000 dmt/year (19.5 MWe scale) to be competitive with diesel generators. The breakeven scales for pyrolysis generators are

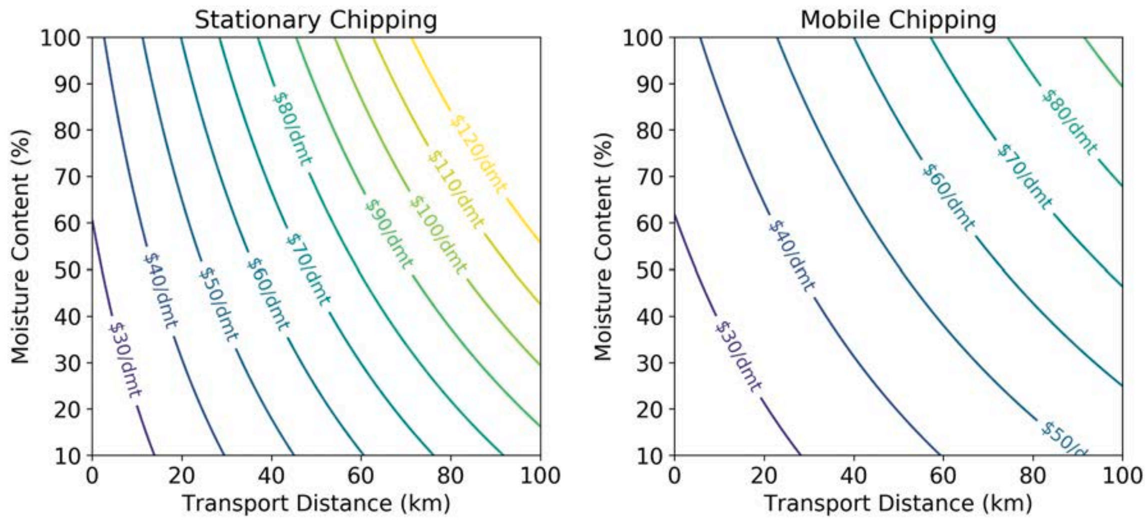

Fig. 4. Delivered costs of stationary (status quo) and mobile chipping pathways for hurricane debris over a range of transportation distances and debris moisture contents. Costs presented in dollars per dry metric ton ($/dmt).

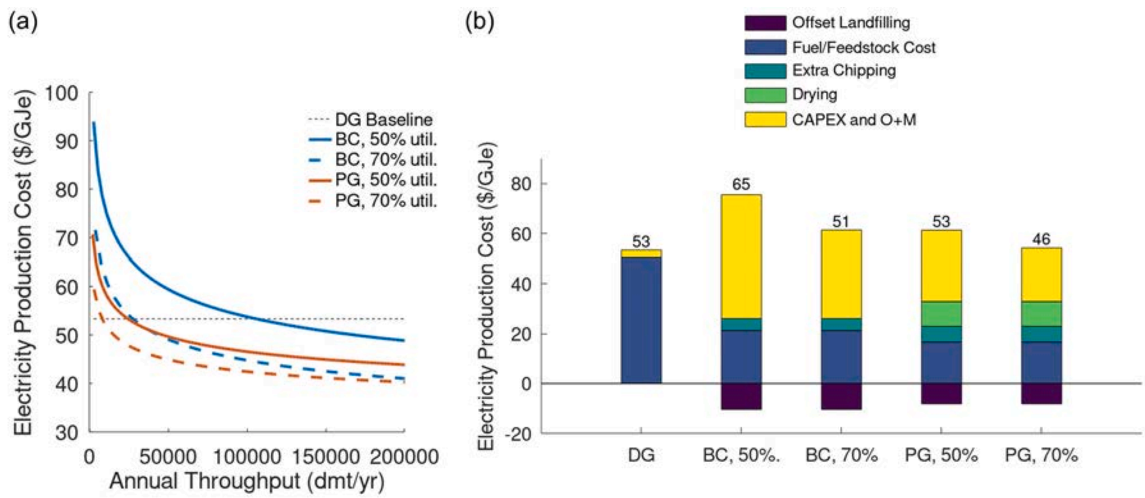

Fig. 5. Electricity production costs for the diesel generator (DG) baseline, boiler combustion (BC), and pyrolysis generator (PG) scenarios modeled at 50% and 70% utilization rates. Values modeled using delivered costs at 80-km distances, 50% moisture content, and $20/ton debris service fee. (a) Dependence of the production cost on annual throughput. (b) Cost breakdown at 5MWe (approximately 25,000 dmt/year) scale, with summed production costs including offset landfilling fees shown at the top of each bar.

9000 dmt/year (1.5 MWe) and 21,000 dmt/year (5 MWe) for 50% utilized and 70% utilized capital equipment respectively. In general, minor hurricane events would generate adequate feedstock for systems utilizing under 50,000 dmt/year - one category 2 hurricane affecting 100,000 people would generate approximately 55,000 dmt of debris [27]. If a dry season were to occur, smaller-scale facilities could be more readily deployed to other regions. The Southern U.S. is estimated to have 500–1000 dry tons per square mile of both forest residues and agricultural wastes available for roadside prices of $60/dry ton [6], and such a backup feedstock would minimize biomass supply uncertainties.

The facility scale would also affect the mobility of the proposed systems. The footprint of ocean barges range from 500 to 1100 m^2 [117]. The 50 kWe Entrade E4, a CHP system that was delivered to Puerto Rico to run off hurricane debris, fits into a standard 20-ft shipping container [118], with a footprint of around 300 m^2 per MWe. Satellite imagery of the 30 MWe Honey Lake Power facility in California shows a 12,000 m^2 footprint (400 m^2 per MWe). While further research should be conducted to specify the barge layout, facilities in the 1-5MWe (5000–25, 000 dm t/yr) range could likely be transported by 1–2 barges.

The sensitivity analyses for the BC and PG scenarios (Fig. 6) show that energy production cost is most sensitive to capital equipment parameters (cost, utilization, and conversion efficiency). 30% changes in capital costs result in $15/GJ and $8/GJ changes in production cost for BC and PG respectively. Moisture content also plays a large role for PG due to the need to dry feedstock down to 10% MC; if incoming PG feedstock had 20% MC instead of 50% MC, the energy production cost would be $10/GJ lower. In general, the results and sensitivity analyses show the need for further specification and refinement of capital equipment, adapted to hurricane debris composition and projected supply.

4.1.3. *Carbon accounting results*

Diverting debris from landfills could also offset significant carbon emissions and result in carbon-negative energy production (Fig. 7). Importantly, biogenic emissions are included in the present model so that they can be compared with decomposition baselines. The non-biogenic process emissions for the BC and PG scenarios are 29 and 69 $kgCO_2e/GJ$ respectively, compared to 741 and 398 $kgCO^2e/GJ$ with

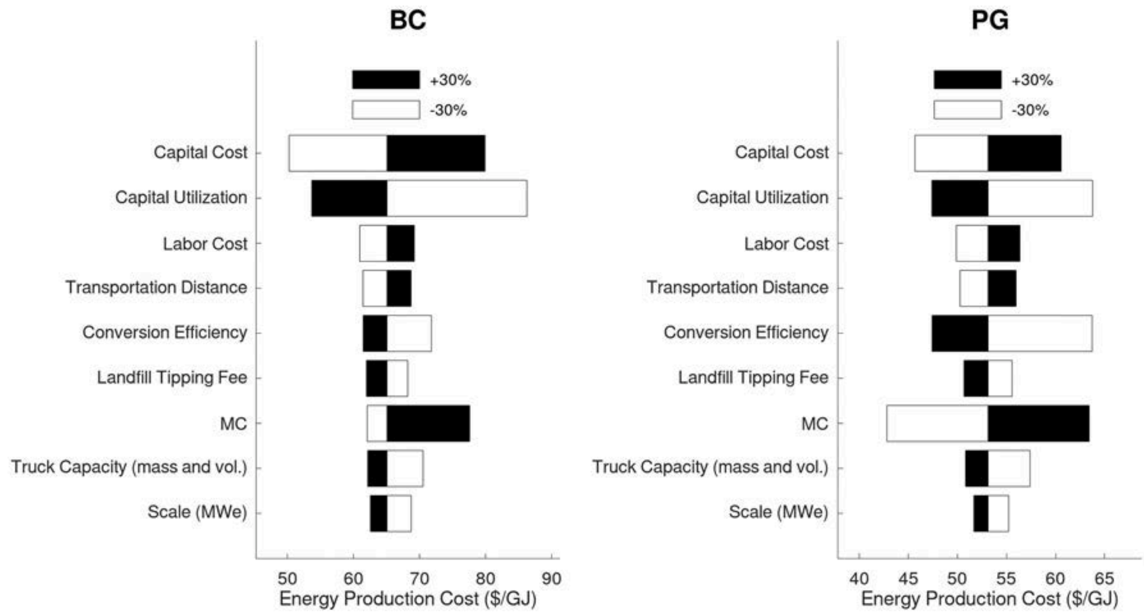

Fig. 6. Sensitivity of energy production cost of the boiler combustion (BC) and pyrolysis generator (PG) scenarios to key parameters for the utilization of hurricane debris. Base values modeled using 80-km transportation distance, 50% moisture content (MC), $20 per ton offset landfill tipping fee, 5MWe scale, and 50% capital utilization.

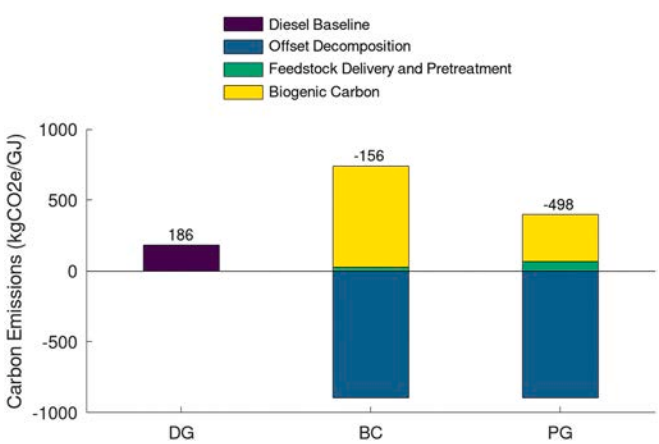

Fig. 7. Net carbon emissions of the diesel generator (DG) baseline, boiler combustion (BC), and pyrolysis generator (PG) scenarios for the utilization of hurricane debris.

biogenic combustion emissions included. If decomposition offsets are included, the boiler scenario offsets 156 $kgCO_2e$ and pyrolysis offsets 498 $kgCO_2e/GJ$.

The decomposition offsets should be refined and quantified in future studies. Some research suggests that wood decomposes on much longer timelines than suggested by the IPCC [119] and could be overestimated by up to a factor of 56 [120]. If the carbon content of landfilled wood is sequestered rather than emitted as methane, bioenergy pathways could be less sustainable than diesel and landfilling baselines, and refining these estimates should be a focus of future work.

Pyrolysis emits less biogenic carbon due to the production of biochar, which sequesters 50–77% of the initial carbon [121] and can be used as a soil amendment [122]. Furthermore, Campbell et al. (2018) found that producing biochar from pyrolysis was more profitable than the co-production of bio-oil and biochar [98]. While biochar could lack real markets in post-disaster scenarios, its potential as a profitable, carbon-sequestering product warrants further work.

Our results show that a properly utilized, small-scale bioenergy facility has lower energy production costs than diesel baselines. Bioenergy pathways are also carbon negative if decomposition offsets are included, and using pyrolysis to generate bio-oil and biochar has the highest emission reduction potential. The modeled pyrolysis facility could have used the 1 million tons of debris generated in Puerto Rico in 2017 [9] to generate 2.4 million GJ of electricity while offsetting 1.2 million tons of CO_2 (representing 3.2% of Puerto Rico's total electricity generation and 6.3% of total emissions in 2016 [123]).

Future research should focus on adapting the present study to more complex debris scenarios. For instance, the techno-economic model assumes that debris is transported 80-km regardless of facility scale. In practice, it may be cheaper to mobilize ten 2 MW units to distributed sites instead of hauling the biomass to a single 20 MW facility. On the other hand, a well-placed, stationary utility-scale system could serve a larger geographic region with a lower capital cost. Although this would require a more robust feedstock supply chain and storage facilities, it is worth noting that a significant portion of American-made wood pellets is shipped across the Atlantic Ocean for $10–15 per ton [58]. A retrofit biomass-coal co-fired plant may also be appropriate for Caribbean countries with high coal dependence. Agbor et al. (2016) found that retrofitting coal plants to co-fire whole tree forest wastes and forest residues cost around $179/kW of installed capacity [124] - significantly less than the boiler or pyrolysis equipment modeled in this study. A co-fired facility could be cost-competitive and serve longer-term sustainability goals if adequate supply chains can be designed.

4.2. Utilization of invasive water hyacinth

4.2.1. Delivered cost results

The transportation model was used to evaluate the costs associated with different modes of water hyacinth transportation. The results at 100-m transportation distances (Table 6) show that cost is reduced by 26% from $26.56 to $19.57 per dmt if the harvester mass capacity is fully utilized and is reduced by 87% to $3.41/dmt if the full motor-propeller power is utilized.

The results show how equipment dedicated to aquatic plant removal could be improved to enable the profitable harvest of water hyacinth. An aquatic plant harvester deployed to Lake Tana in 2018 takes 15 minutes per load due to deck volume constraints [50], and similar harvesters

Table 6
Carrying capacity, specific cost, fuel consumption, and carbon emission results for transporting water hyacinth.

	Boat-pack	Boat-pack w/ vol. reduction	Boat-pack
Capacity Restriction	Deck Volume	Deck Mass	Tow Capacity
Carrying Capacity (dmt/trip)	0.066	0.095	0.583
Specific cost ($/dmt)	$26.56	$19.57	$3.41
Specific fuel consumption (L/dmt)	4.4	2.1	1.0
Specific carbon emission (kgCO_2e/dmt)	11.7	5.8	2.8

have been reported since the 1970s [125,126]. Simply equipping these harvesters with *in situ* volume reduction could reduce fuel consumption by 52% and carbon emissions by 50%. This could be achieved with *in situ* roller crushers which crush plants on the water [127] or with on-board shredders [128]. Additionally, while thick mats of water hyacinth can impede machine performance, they could also be used for more effective gathering or towing - for example, Hronich et al. (2008) suggested that mats could be cut in strips, secured with grappling hooks, and towed to shore [129]. The results of this study suggest that this approach could be further enhanced by packing water hyacinth into expanding-in-length bags in a manner similar to packing and storing silage [130].

4.2.2. Techno-economic analysis and carbon accounting results

The costs and emissions of producing useful cooking heat from biogas (BG) from anaerobic digestion of water hyacinth are compared to traditional wood stove baselines (WS) (Fig. 8). The results show that even with no fertilizer revenue, biogas can produce useful heat for $15/GJ compared to wood at $31/GJ. Once fertilizer revenues are added in, heat production costs drop to -$9/GJ - showing that fertilizer revenues alone could exceed total production costs. The BG scenario emits 4 kgCO_2e of fossil emissions and 130 kgCO_2e of biogenic emissions per GJ useful heat, compared to 570 kgCO_2e/GJ biogenic emissions in the WS scenario. After decomposition offsets are included, the BG scenario offsets -3 tons of CO_2 per GJ.

The sensitivity analysis (Fig. 9) shows that energy production costs are most sensitive to volume reduction (which affects delivered costs and digester throughput) and fertilizer revenues. Because of the low nominal density of water hyacinth, even 30% differences in volume can result in $9/GJ differences in energy production cost, highlighting further the need for volume-reduction equipment innovations. The fertilizer revenue, which is credited per ton of water hyacinth throughput, is so significant that conversion efficiency appears to inversely affect production costs because more energy is produced from less water hyacinth (and thus less fertilizer slurry can be sold). In practice, higher conversion efficiencies in an anaerobic digester would likely lead to shorter residence times, higher throughputs, and higher quality digestate slurry.

Future work should include the impacts of locale-specific feedstock quality and markets. For instance, biogas produced from water hyacinth could contain hydrogen sulfide gas and the cost of a scrubber may have

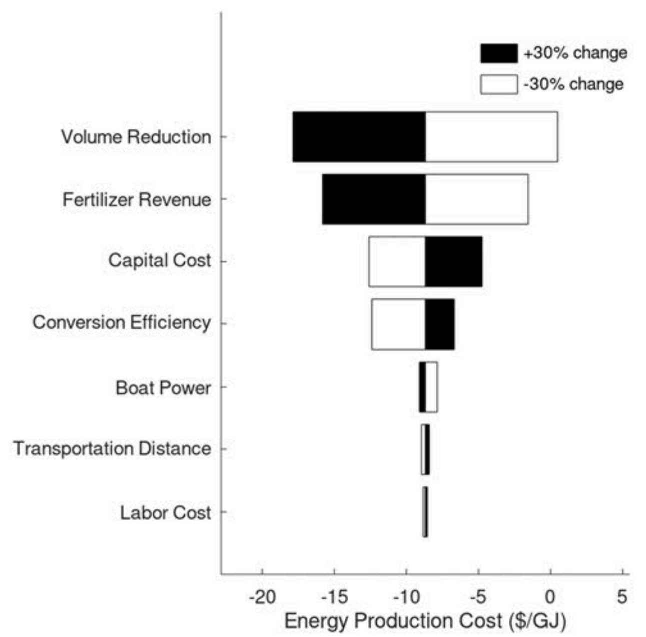

Fig. 9. Sensitivity of energy production cost of the biogas (BG) scenario to key parameters for the utilization of water hyacinth. Base values modeled using 100-m transportation distance, 70% volume reduction, and $2.26 per ton fertilizer revenue.

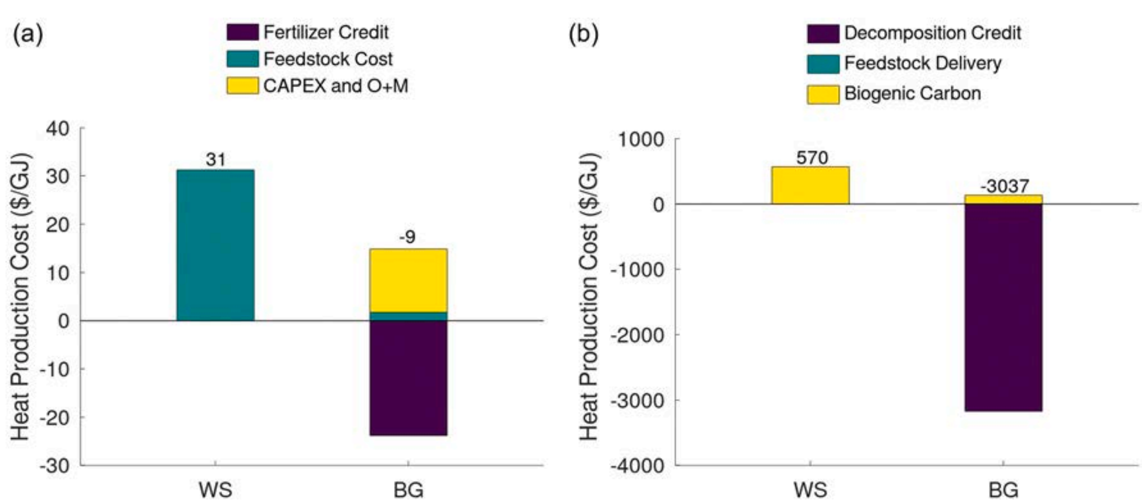

Fig. 8. (a) Heat production cost of the wood stove (WS) baseline and biogas stove (BG) scenarios for the utilization of water hyacinth. (b) Heat production emissions of the WS baseline and BG scenarios.

to be included [131]. However, the removal of sulfides and other heavy metals would improve water quality [132] and profitable water hyacinth utilization could enable downstream innovations, such as in the use of WH-derived carbon materials to remove hydrogen sulfide and ammonia from produced biogas [133].

If half of the 40,000 hectares of water hyacinth on Lake Tana were kept as a standing crop, 4.8 million MJ of useful energy could be produced from 2800 dmt of daily growth [73], replacing the cooking needs of 440,000 households [85]. In Ethiopia, biomass accounts for 91% of consumed energy [134] and increased fuelwood usage has led to increased deforestation and forest degradation [135]. A profitable biogas operation could reduce dependence on fuelwood, reduce air pollution, provide a source of useful fertilizer slurry, and create jobs [136]. Furthermore, replacing fuelwood could save families 1–3 h per day spent gathering wood for cooking [84]. Such additional social benefits are significant but are not included in modeled results.

Despite these benefits, the penetration of digester technology in lower-income regions such as Sub-Saharan Africa is low. This is potentially due to high construction costs [95], changing manure supply, or technical breakdowns [136]. Successful digester installations may require innovative financing or government support; however, by co-locating with existing, expensive cleanup operations, a digestion operation could utilize funds previously allocated for water hyacinth control. For instance, the $70,000 spent on a harvester for Lake Tana [137] could have been used to finance similar machinery that utilizes hyacinth instead of leaving it on shore to decompose [50]. Ultimately, the presented results show that mobile processing and utilization of invasive and fast-growing plants could be profitable, given the right labor conditions and technology.

5. Recommendation of future work

The techno-economic analysis and carbon accounting presented in this work can be further enhanced to enable commercial utilization of endemic wastes. The specific process and model parameters should be refined once a target feedstock and geographical region are chosen. For instance, the market value of co-products such as biochar and digestate slurry should be defined, and the use of co-produced heat to dry incoming debris or to pre-heat feedstocks for pyrolysis or anaerobic digestion should be explored. The logistics and labor costs of transporting co-products, feedstocks, wastes, and diesel fuel will be scale- and site-specific. Furthermore, the effects of changing machine and equipment parameters should be further quantified, for instance by using higher-power chippers, larger aquatic harvesters, or differing types of on-water towing bags.

The broader societal benefits of the proposed systems should also be evaluated, such as by evaluating the Societal Impact Factor (SIF) [138]. Traditionally, disaster-hit economies devote scarce fuels to cleanup efforts while traditional energy streams are repaired. On the other hand, this work proposes solutions that would employ local debris crews, domestically produce fuel or electricity, reduce dependence on imported fossil fuels, and divert wastes from landfills. Similarly, utilizing naturally-overgrown aquatic plants could stimulate fishing economies, improve local water quality, and increase access to clean cooking fuel or electricity while employing local communities. The determination of the actual social value is beyond the scope of this paper, but future work must consider far-reaching effects such as the offset of job loss or economic decline from reduced cleanup costs.

6. Conclusion

This study develops techno-economic models that contribute to the utilization of hurricane debris and invasive water hyacinth, two problematic biomass sources that typically cause costly cleanup efforts. Bioenergy conversion that simultaneously alleviates cleanup costs and produces valuable fuels is a niche that pushes the technologies toward profitability.

Specifically, results show that:

- Using hurricane debris, electricity generation from biomass boilers at 4 MW (30,000 dmt/yr) scales and pyrolysis generators at 1.5 MW (9000 dmt/yr) scales are cheaper than diesel fuel baselines, if 70% utilization of the capital equipment can be maintained. Bioenergy pathways emit less carbon than diesel energy if biogenic carbon emissions are excluded, and are carbon-negative if full decomposition offsets are included.
- The anaerobic digestion of water hyacinth could produce useful cooking heat for a net profit of $9/GJ if fertilizer revenues are included, with production emissions of 134 to −3037 $kgCO_2e/GJ$ depending on decomposition emission offsets.
- Increasing transportation vessel capacities (trucks and boats) can reduce delivered costs by 30–87% depending on transportation distance, due to decreases in the total number of trips required.

The proposed systems could consume debris, offset landfill costs and emissions, and produce valuable and cost-effective bioenergy. In the case of hurricane debris, results show that a facility must be carefully designed to maximize utilization and optimize scale in order to react to uncertain feedstock supplies. On the other hand, a standing water hyacinth crop would be consistent but would require innovations in harvester equipment to be profitable. The potential of these endemic wastes to generate local energy, economic profit, and carbon offsets warrants further study and development of experimental systems to test and evolve the hypotheses.

The inevitable generation of huge quantities of hurricane debris and invasive water hyacinth calls for solutions that can turn these feedstocks into opportunities for positive and profitable impact. The future of clean, locally produced, globally available energy requires carefully designed and evaluated biomass utilization systems, and this work contributes to this future by demonstrating the potential of endemic waste-to-energy systems to be economically profitable and environmentally friendly.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Covid-19 shock: Development of strategic management framework for global energy

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ABSTRACT

Energy resources are vital for the economic development of any nation, and they are currently recognised as an essential commodity for human beings. Many countries are facing various levels up to severe energy crisis due to limited natural resources, coupled with the Covid-19 pandemic. This crisis can lead to the shutdown or restriction of many industrial units, limited energy access, exacerbating unemployment, simultaneous impacts on people's lives. The main reason for these problems is the increasing gap between energy supply and demand, logistics, financial issues, as well as ineffective strategic planning issues. Different countries have different visions, missions, and strategies for energy management. Integrated strategic management is requisite for managing global energy. This study aims to develop a strategic management framework that can be used as a methodology for policymakers to analyse, plan, implement, and evaluate the energy strategy globally. A conceptual research method that relies on examining the related literature is applied to develop the framework. The present study yielded two main observations: 1) The identification of key concepts to consider in designing the strategic management framework for global energy, and 2) A strategic management framework that integrates the scope, process, important components, and steps to manage global energy strategies. This framework would contribute to providing a standard procedure to manage energy strategies for policymakers at the global, regional, national, state, city, district, and sector levels.

1. Introduction

Energy has a vital role in human life. It supports the development of various sectors, including industry, agriculture, telecommunication, and transportation [1]. Bilgen [1] stated that energy is defined as the strength and capability required for doing activities. The type of energy is diverse such as electrical, thermal, gravitational, sound, chemical, radiant, nuclear, and elastic. Energy sources are classified as non-renewable and renewable energy. Non-renewable sources of energy consist of fossil fuels (coal, natural gas, petroleum) and uranium. Renewable sources of energy refer to solar energy, wind turbines, geothermal, biomass, and hydropower [2].

Energy use in most countries increases over the time due to social and lifestyle changes [3], architectural and urban designs that are not environmentally friendly [4], and the growth in population in a country [5]. Butler et al. [6] found that consumer activities directly impact on energy consumption. Lifestyle in big cities is energy-intensive, and people are conspicuous and excessively consumptive [7]. Improved living standards have increased consumer demand, thereby increasing energy demand quickly, which is causing growth in carbon emissions [8].

European Union [9] observed that energy consumption of the world in 2018 reached 9938 Mt of oil equivalent (Mtoe). This growth was primarily driven by China, the United States, and India, which together account for about two-thirds of the growth. The highest amount of energy consumed by China, which reached 2067 Mtoe. Depending on the most recent historical average, the most remarkable growth is in the United States. The report showed that energy consumption in the United

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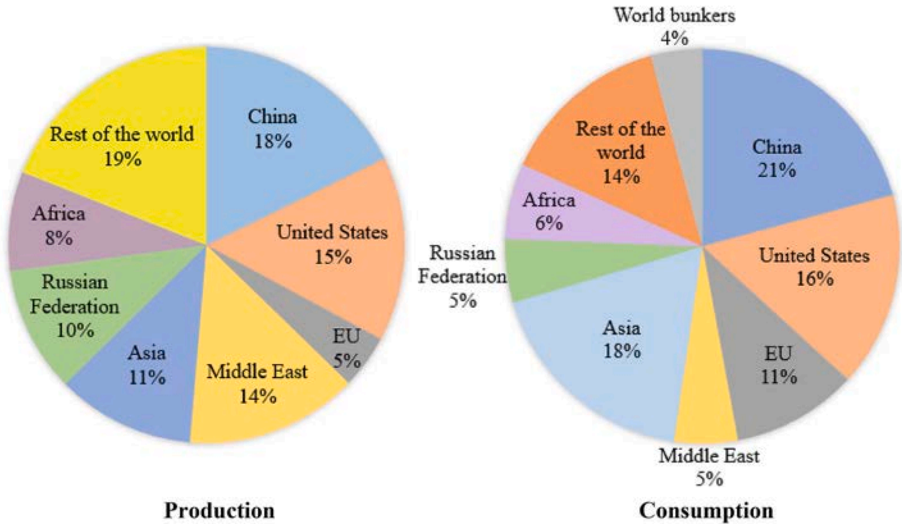

Fig. 1. Global energy production and consumption by region [9].

States reached 1594 Mtoe. In Europe, it reached 1023 Mtoe in 2018. In Asia (non-OECD and OECD Asia, excluding China), final energy consumption reached 1795 Mtoe. Energy use in the Middle East reached 519 Mtoe. The amount of energy consumption obtained by Russia reached 514 Mtoe.

Given the challenges of the new millennium for faster modern socio-economic development and the adoption of new lifestyles, industrial development imposes very high energy production [1]. The forecasts indicate that energy production will keep increasing [10]. EU report [9] observed that China is ranked as the most top energy-producing country in the world, reaching 2562 Mtoe in 2018. The second rank is occupied by the United States, which produced 2173 Mtoe of energy. In the Middle East, ultimate energy production reached 2040 Mtoe. Energy production in Europe reached 628 Mtoe. In Asia, it reached 1631 Mtoe in 2018. Fig. 1 shows the statistics of global energy production and consumption.

The strength in energy consumption is practically reflected throughout all fuels, and the majority of them grow more robust than historically average. BP report [10] argued that global primary energy increases by 2.9% in 2018, which is the fastest growth since 2010. This phenomenon happened amidst the background of modest Gross Domestic Product (GDP) growth and rising energy prices. At the same time, carbon emissions from energy use grow by 2%. This amount shows the fastest expansion in years, with emissions increasing by around 0.6×10^9 t.

Global energy production and consumption can be influenced by many aspects, such as economic, political, technological, environmental, and social. One case that occurred was the COVID-19 coronavirus pandemic which affected the global energy sector, such as a drastic decline in oil prices and demand, increased global CO_2 emissions, energy supply shock, and unemployment. These issues lead to the global energy crisis problem.

A fluctuation in energy demand that is not in balance with its production, followed by a significant increase in energy prices and emissions, shows an unclear energy vision. Global energy resources should be managed using strategic management to attain the identified goals and objectives. In the process, the policymakers need to formulate strategies that allow them to attain better performance and competitive advantage.

Global energy intensity is an indicator used to track progress on global energy efficiency. International Energy Agency [11] mentioned that the initial target is to reduce annual energy by 2.6% until 2030. However, the rate of increase in global energy intensity is only 1.7% in 2017, and an increase to 2.7%/y is needed until 2030. In 2018, an increase in global energy intensity was only 1.2%. This means that from 2019 to 2030, global energy intensity has to increase again by 2.9% every year to reach the sustainable development goals and targets. A substantial step is required in planning and implementing energy efficiency strategies and policies to achieve this goal.

The strategic management process for global energy determines where the global energy transition has to go, why this transition has to go there when the humans have to go there, and how to get there [12]. In doing so, the policymakers should have a long-term plan that involves decision-making processes in all levels, including global, regional, national, state, city, district, and sector [13]. This long-term plan requires a method that demonstrates the process of designing strategic management for global energy. Current efforts focus solely on strategic management for a country [14]. Different states have different visions, missions, and strategies for energy management according to their benefits [15]. In supporting the development of sustainability, nations should consider the sustainability aspect in their strategic management [16]. In reality, sustainability embedment in strategic management for global energy is still relatively low [17]. There is a need for global-level strategic management that integrates the vision, mission, and strategies of all countries so that the production and consumption of all energy sources can be sustainable and meet all the needs of the community.

From an academic point of view, research on strategic management for global energy is still limited in number. Prasad et al. [13] argued that there is no strategic energy planning available at the global level due to a lack of international governments. Existing studies only emphasise on one source of energy, such as renewable energy [18], crude oil [19], and fossil [20]. Some other existing studies focused on one sector, such as the power sector [21] and manufacturing [22], and one aspect of strategic management, such as politics [23] and resources [24].

Based on this argument, this study aims to develop a strategic management framework that can be used as a methodology for policymakers to analyse, plan, implement, and evaluate the energy strategy globally. This framework embroils strategy analysis for all types of energy (renewable and non-renewable energies) and various aspects of strategic management, including scope, process, models, and methods. The scope of the methodology should cover all levels of stakeholders in global energy management including global, regional, national, state, city, district, and sector to align all strategies for energy as a whole. This idea is intended to avoid managing an energy strategy that only focuses on the interests of a country or region, unfair competition for resources, unequal increases in certain energy prices, and exploitation of energy production in certain countries or regions.

This study applies a conceptual research approach to develop the proposed framework through an in-depth examination of related literature. This study yielded two main observations: i) The identification of key concepts to consider in designing the strategic management framework for global energy, and ii) Development of a strategic management framework that integrates the scope, process, model, and method to manage global energy strategies. The proposed framework considering general features of strategic management methodology that can be useful for energy producers, suppliers, and customers (international institutions, national government, equipment manufacturers and retailers, energy supply companies, facilities management companies, energy services companies, and energy producers) to grasp the essential aspects in developing energy strategies in the international and national scope. Specifically, the proposed methodology can be adopted by policymakers at the global, regional, national, state, cities, districts, and sectors, such as intergovernmental organisations and government agencies, as a guide for analysing, formulating, implementing, and evaluating energy strategies globally.

The structure of this paper is classified as follows. Section 2 analyses the pertinent literature on strategic management for global energy and reveals the knowledge gaps. Section 3 describes the methodology used to attain the research objective. Section 4 presents the development process of the strategic management framework. Section 5 discusses the main results obtained and their imperative for managing global energy. Section 6 concludes the study by delivering research contributions and future research opportunities.

2. Literature review

This section discusses some concepts associated with strategic management for global energy and reviews existing studies in the field of strategic management for energy. This process is useful to identify related concepts used for strategic management for energy at the global scale and reveal the knowledge gaps and contradictions in the existing study. The literature analysis is categorised into two parts: concept explanation related to strategic management for global energy and research review on strategic management for energy. The concept related to strategic management for global energy includes scope, strategic management process, and model. The analysis of the existing study on strategic management for energy includes contents and methodology review. Fig. 2 presents the categorisation of literature in this study.

2.1. Concepts related to strategic management for energy

This study identified several related concepts about strategic management for global energy. The first concept is the scope, which refers to the range or area of the policymaker plans to offer the strategy. The second concept is the strategic management process, which shows a coherent approach used by policymakers to attain strategic competitiveness and to get above-average returns. The third concept is the strategic management model, which shows the important elements to consider in strategic management for global energy. Each of these concepts is discussed in the following sub-sections.

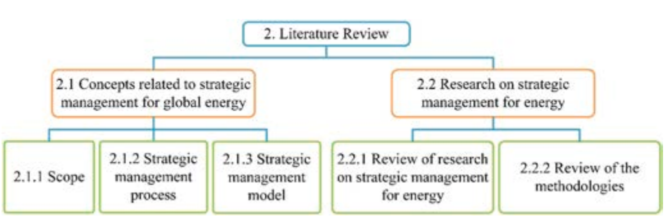

Fig. 2. The structure of the literature review.

2.1.1. Scope

In achieving sustainable improvements in global energy management for the long-term, policymakers need a strategic management methodology to design, implement, and evaluate energy strategies globally [25]. This methodology should have a broader scope of strategy covering global, regional, national, state, city, district, and sector [13] to avoid some strategic issues including designing and implementing energy strategies that only focuses on the interests of a country or region, unfair competition for resources, unequal increases in certain energy prices, and exploitation of energy production in certain countries or regions. Having a long-term view on energy conservation and energy management globally, which includes the use of environmentally responsible and cost-effective energy throughout the world, makes it possible to continue to improve energy management in operations [26]. This process involves all key stakeholders in managing global energy [27]. Practitioners should ensure to meet customer requirements regarding energy utilisation, analyse, and communicate progress and success in energy innovation to internal and external stakeholders [28].

In global energy planning, classification of energy sources are based on suppliers and customers, and the data obtained and analysed has to be complete and reliable, which will later be integrated into a global energy system [29]. European Environment Agency [30] mentioned that policymakers need to understand the implications of selected energy, environmental and economic programs, policies and plans, and their impact on the formation of development and on the feasibility of making this development sustainable. This energy indicator is more than just energy statistics because it provides a deeper understanding and association about energy, the environment, and economic relations.

Prasad et al. [13] stated the importance of a nation to comprehensively see its needs for energy sources from internal and external sources. A nation needs to examine the supply chain of energy sources to predict risks and opportunities. A nation also needs to know and control energy costs and analyse energy suppliers because this affects the daily lives of people and businesses. The nations that have energy sources as the backbone of their economy need a comprehensive strategic management method to predict and control their competitors and the prices of energy sales. For this reason, energy planning needs to consider the geographical level consisting of global, national, regional, city, and district.

Krog and Sperling [25] argued that a strategic energy plan should embrace all levels in the energy system. They believed that long-term energy planning has to encourage sustainable development that is adequate and available at a reasonable cost to meet people's energy needs without having negative social and environmental impacts. This study summarises the scope, process, and output of global strategic energy planning, as given in Fig. 3.

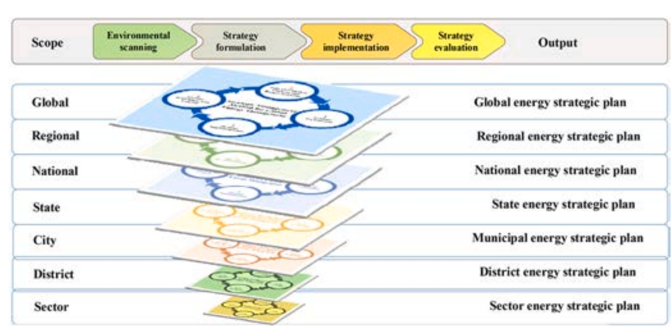

Fig. 3. Schematic representation of a global strategic energy management.

2.1.2. Strategic management process

Strategic management has a vital role in managing global energy [31]. This concept helps policymakers achieve sustainable improvements in energy performance over a long-term period [32] to reduce energy consumption through increased energy efficiency and energy conservation [31]. The long-term strategy also improves the highest demand management and reduces demand costs, reduces overall energy costs, increases reliability through the integration of distributed energy resources, and reduces greenhouse gas (GHG) emissions [33]. The application of strategic management concepts and tools in global energy management enables the practitioners to set long-term energy planning and predict the future trends of global energy production and consumption.

Krog and Sperling [25] mentioned that strategic energy planning has to secure future energy systems that are energy-efficient and flexible. Strategic energy planning includes all possible elements of the global energy plan, stakeholder coordination, and security of supply strategies. International governments has to carry out strategic energy planning to create optimal interactions between energy demand and energy supply in such a way that energy resources are used optimally.

The strategic management process provides a logical procedure for defining strategies [34]. This process enables decision-makers to analyse the current situation and assess future directions to get better performance [35]. The strategic management process is an iterative procedure that includes several steps, including scanning the current situation, formulating strategies, implementing strategies, and evaluating strategies [36]. Each stage contains several key components that need to be considered in the strategic management process. Fig. 4 provides the steps of the strategic management process.

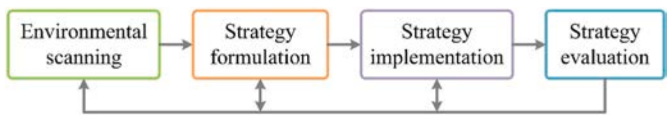

Fig. 4. Strategic management process (adapted from Hitt et al. [36]).

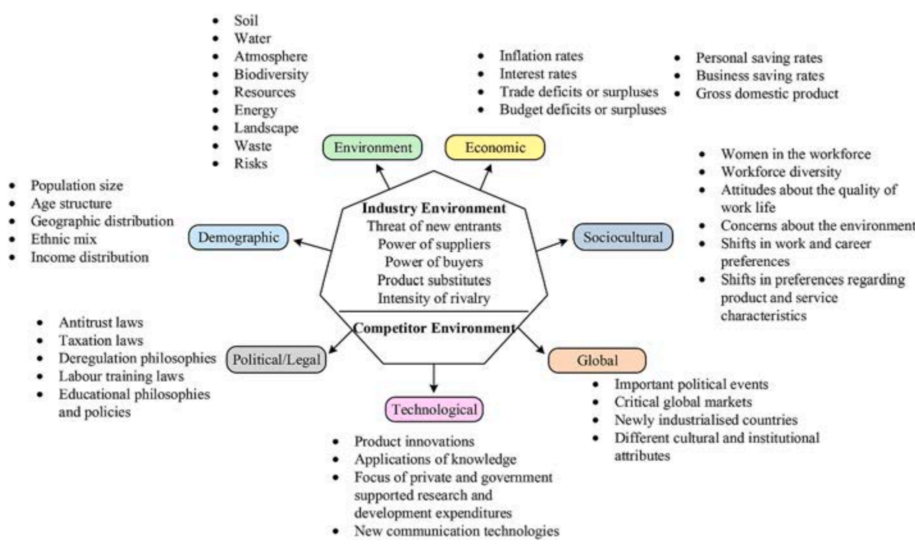

Fig. 5. The I/O model (adapted from Hitt et al. [36] and Global Reporting Initiative [47]).

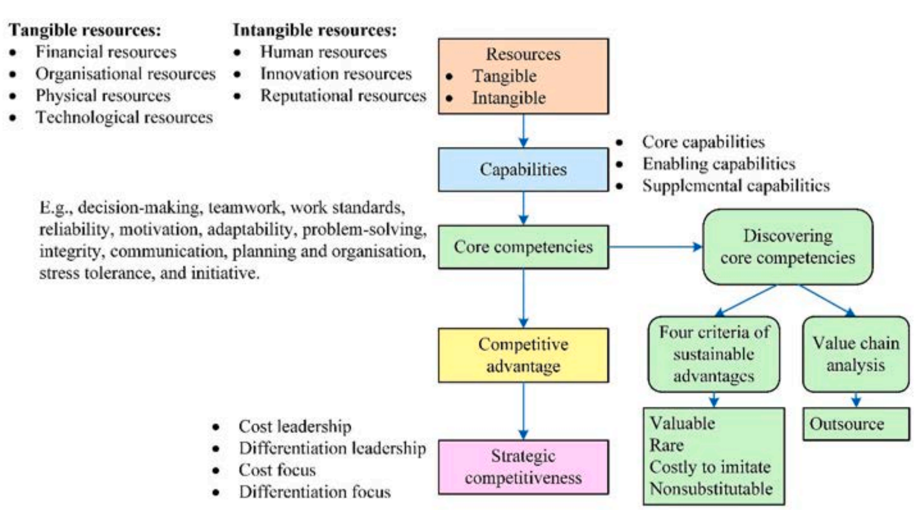

Fig. 6. The resource-based model (adapted from Hitt et al. [36], Plank and Doblinger [49], Porter [50], and Achinas [51]).

Table 1
Summary of research on strategic management for energy in the scope of global, regional, and national.

Reference	Research focus	Methodology
Bilgen [1]	Investigate global energy consumption, energy security, and energy policy.	Review
British Petroleum [10]	Report global statistics on energy demand and carbon emissions.	Statistical review
Energy Information Administration [50]	Collect, investigate, and publish global energy information.	Statistical review
European Commission [9]	Report global and European statistics of energy supply and use.	Statistical review
Jonsson et al. [52]	Identify a complete set of energy security features for measuring low-carbon energy scenarios.	Review
Krog and Sperling [25]	Propose a framework for analysing strategic energy planning in Denmark.	Conceptual research
Terrados et al. [54]	Analyse current energy planning and propose a new methodology to plan renewable energy strategies.	SWOT analysis, multi-criteria decision analysis, and Delphi method
Ervural et al. [55]	Propose a hybrid methodology to analyse energy planning and management in Turkey.	Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis.
Tagliapietra [53]	Investigate the effect of the global energy transition on economics and politics in the Middle East and North Africa.	Review
Tofigh and Abedian [56]	Analyse energy production, consumption, export, and import in Iran and identify their strengths and weaknesses.	Review
Alizadeh et al. [14]	Introduce an integrated scenario planning method for energy management in Iran.	Scenario thinking process
Chen and Wu [57]	Study global energy consumption to provide strategic allegations for sustainable energy policymaking.	Statistical review
Wu and Chen [58]	Examine the global consumption of crude oil.	Statistical review
Abbaszadeh et al. [59]	Analyse energy status in Iran and develop scenario planning based on production and consumption.	Scenario thinking process
Mollahosseini et al. [60]	Provide a general idea of the current status and demands of renewable energy management in Iran.	Statistical review
Achinas et al. [51]	Analyse the biofuels energy industry and discuss the interrelation between the technological aspect and sustainability.	PESTLE analysis

1. Environmental scanning

The external and internal environment should be scanned to determine the development and forecasts of factors that will influence the success of the organisation [37]. Olamade et al. [38] mentioned that environmental scanning refers to the ownership and utilisation of information about events, patterns, trends, and relationships in the organisation's internal and external environment. It helps the policymakers to decide on the upcoming path of the organisation. In the scanning process, they need to identify the strengths, weaknesses, opportunities, and threats factors that impact on the new system implementation [39]. The techniques for scanning the environment that is generally used by experts consist of the Strengths Weaknesses Opportunity and Threats (SWOT) analysis and Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) analysis [40].

2. Strategy formulation

Strategy formulation refers to the process of planning a strategy and choosing the right actions to implement the strategy and realise the goals and objectives of the organisation in accordance with the vision [41].

3. Strategy implementation

Strategy implementation is the implementation of the chosen strategy into organisational action to achieve strategic objectives [42]. Strategy implementation is also defined as the process by which practitioners develop, utilise, and combine organisational structures, control systems, and culture to follow strategies that lead to better performance and competitive advantage [43].

4. Strategy evaluation

Strategy evaluation is the final stage of the strategy management process. In this process, practitioners need to evaluate and control the implementation of the strategy [44]. Some important things to do in evaluating the strategy include the suitability of the strategy with the objectives that have been identified [45]. The practitioner also needs to evaluate whether the strategy meets the expectations of the stakeholders [46].

2.1.3. Strategic management model

The strategic management model used to generate the strategy consists of an industrial organisation (I/O) model of above-average returns and a resource-based model [36]. The I/O model encompasses

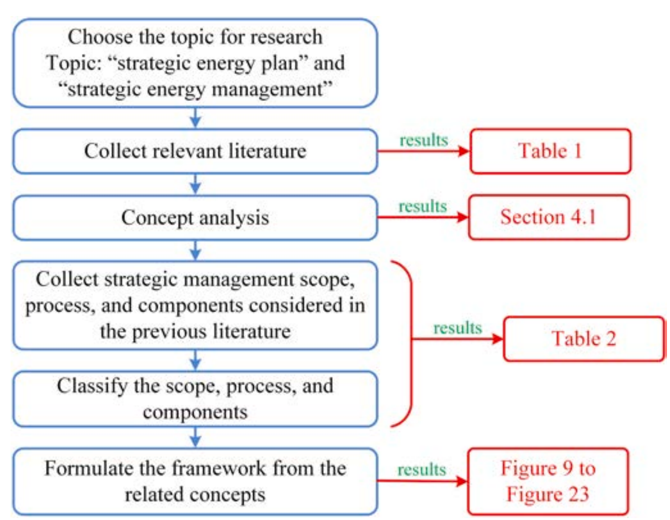

Fig. 7. Stages in conceptual research method (adapted from Chofreh et al. [64]).

an analysis of the external environment (economic, sociocultural, global, technological, political/legal, demographic, and environmental factors) and industry environment (suppliers, customers, and competitors) [43]. The resource-based model consists of the identification and analysis of the internal environment, including resources (liquid fuels, natural gas, coal, nuclear, and renewables), capabilities, core competencies, and competitive advantage [43]. The categorisation of the strategic management model is consecutively given in Figs. 5 and 6.

The I/O model is considered as a primary component in strategic management that should be analysed to achieve an effective strategy [36]. White [48] stated that this model influences decisive action as it helps policymakers to determine threats and opportunities from all aspects of the external environment. It challenges management to compete because most organisations are supposed to have valuable resources, and their performance can be increased if they can use the resources optimally to implement the strategy.

The resource-based model assists the policymakers to analyse the internal environment of an organisation [43]. Hitt et al. [36] explained that the main components of this model include resources, capabilities, and core competencies. Resources are related to tangible and intangible inputs for the production process, such as capital, skills, and raw materials. A capability refers to a set of resources to perform an integrated activity. Core competencies are resources and capabilities that serve as a basis of competitive advantage for an organisation over its competitors. In the resource-based model, the performance of an organisation depends on its resources and capabilities.

2.2. Research on strategic management for energy

This section provides the literature analysis to understand better the focus of the current study on strategic management for energy and to identify the inconsistencies in the literature. This step is conducted by analysing the existing research based on two paradigms: content and methodology. The process and its results are explained in the following sub-sections.

2.2.1. Review of research on strategic management for energy

Research on strategic management for energy has emerged as a subject of significant scholarly attention. Even though the topic under this research is various, the majority of them focused on energy strategies for specific regions or countries. For example, Jonsson et al. [52] investigated the strategy aspects of energy security in the EU countries. They found that security of demand security and geopolitics are essential for transforming low-carbon energy. Other important aspects are related to future global climate agreements and international relations, which have a significant influence on security energy transfer in the EU. Another study conducted by Krog and Sperling [25] analysed numerous vital aspects to improve strategic energy planning for renewable energy systems in Denmark, which culminated in a conceptual framework. They considered several issues, including levels and elements in strategic energy planning, and various tools and methods to analyse them. Tagliapietra [53] discussed an energy transition in the Middle East and North Africa. They observed that the global energy transition might be a positive input for hydrocarbon producers based on economic and political aspects.

Since energy studies on a global scope are still sparse, the present study broadens the scope of studies by focusing on strategic management for energy on a global, regional, and national. This literature analysis helps identify key components in strategic management concept that needs to be considered for managing global energy, including process, model, and methodology. Table 1 provides an overview of the study on strategic management for energy with the identification of critical components and sub-components in the strategic management concept.

Table 1 shows the components and sub-components of strategic management adopted in the existing studies. The analysis reveals that studies focusing on global energy are still relatively small. The majority of the study in this topic emphasises on strategic planning at regional and national levels. Other components considered in the study are strategic management processes and models; however, their sub-components are not completely considered. This idea can be seen in the work of Bilgen [1] that studied some factors instigating the growth of energy consumption based on resources. The author conducted a statistical analysis to investigate the relationship between energy consumption and economic growth. A similar study conducted by Jonsson et al. [52] that scanned and scoped out energy security in Europe from several aspects, including political, sociocultural, economic, technological, and environmental. This gap motivates the present study to consider a more comprehensive suite of components and sub-components of strategic management to get an effective global energy strategy. The method should cover the following features:

i. It should integrate relevant aspects of strategic management into a unified form,
ii. It should provide sequential stages of how to develop global energy strategic management,
iii. Each aspect should have a breakdown structure.

2.2.2. Review of the methodologies

This section discusses the methods used in the existing strategic management for energy studies. Table 1 shows various methods adopted in the study, consisting of review, statistical review, conceptual research, SWOT analysis, scenario development, and PESTLE analysis. The application of the methodology determined by the research question that the study attempts to respond [61]. Each method has its logical basis and limitations so that none of these methods is considered superior to the other. For instance, review methods are used to encapsulate the current state of understanding of a research area [62]. This method is more likely to be used to investigate and summarise existing studies than to analyse and reveal new concepts. A review study shows things such as academics who are experts in their fields, the latest discoveries and innovations, knowledge gaps that are important to analyse, issues being debated, and ideas for future studies [63].

A statistical review is a type of review paper that includes rigorous statistical and data analysis related to a topic [57]. It allows scholars to collect and analyse the data and produce the information systematically [58]. Chofreh et al. [64] discussed that conceptual research method emphasis the concept or theory that describes the phenomenon being studied. This method is appropriate for answering “what” and “how” research questions. This method is generally used to develop a new concept by observing existing related studies.

Another approach used in the field of strategic management for energy is a SWOT analysis. Ervural et al. [55] stated that this technique is typically used to identify and assess the strengths, weaknesses, opportunities, and threats factors involved in making a business decision. This process is performed before committing to any business actions, explore new initiatives, improve internal policies, and consider existing opportunities. The primary purpose of SWOT analysis is to formulate new strategies that extricate the business from competitors and successfully compete in the marketplace.

Scenario thinking, also known as scenario planning, is a systematic process to anticipate and forecast future business decisions due to the increased technological and social change, and an unpredictable future [14]. The objectives of scenario thinking are fostering useful strategic conversations among stakeholders, enhance responsiveness to emerging challenges and opportunities, align strategic planning activities across the organisation, generate and assess innovative strategies and options, and build a deep understanding of business environment drivers [57].

3. Methodology

This study aims to answer the question of "What are the steps for managing global energy strategy?". Conceptual research is considered as a suitable methodology to answer this question. This method is generally used to develop a novel concept or interpret existing ideas from a different viewpoint. It is a fundamental technique in the grounded theory research providing thorough literature analysis [64]. Fig. 7 portrays the general stages in the conceptual research method.

The first stage in the conceptual research method is to choose the research topic based on its significance and knowledge gaps [64]. Strategic management for global energy is selected as a research topic that needs to be observed; however, the study in this area is still narrow. The topics discussed are mostly related to strategic energy planning in a specific region and energy resource. This research would be useful for academics to broaden the scope of research related to energy management.

The second stage is a collection of relevant literature in the area of "strategic energy plan" and "strategic energy management" [64]. This literature search is conducted in several scientific databases, including Science Direct, Google Scholar, and Scopus. The results show numerous published articles in those two research areas in various journals. The present study limits the search time by selecting papers from high impact journals consisting of Renewable and Sustainable Energy Reviews, Journal of Cleaner Production, Energy Strategy Reviews, Technological Forecasting and Social Change, Energy Policy, and official reports.

The third stage is analysing the relevant concept that needs to be envisaged for developing the strategic management framework for global energy. The concept is derived from the literature analysis that exposes an idea to formulate the framework.

The fourth stage is collecting the strategic management components considered in the previous literature to get a general idea in developing

Table 2
Concepts adopted in the existing studies.

Reference	Scope	Process	Model	
			I/O Model (external environment)	Resource-based model (internal environment)
Bilgen [1]	Global	Environmental scanning	Economic Political/legal	Resource
British Petroleum [10]	Global	Environmental scanning	–	Resource
Energy Information Administration [26]	Global and regional	Environmental scanning	–	Resource
European Commission [9]	Global and regional	Environmental scanning	–	Resource
Jonsson et al. [52]	Regional	Environmental scanning	Political/legal Sociocultural Economic Technological Environmental	Resource
Krog and Sperling [25]	National	Environmental scanning Strategy formulation	Political/legal	Resource
Terrados et al. [54]	Regional	Environmental scanning Strategy formulation	Technological Environment Sociocultural Economic	Resource
Ervural et al. [55]	National	Environmental scanning Strategy formulation	Economic Sociocultural Technological Political/legal Demographic	Resource
Tagliapietra [53]	Regional	Environmental scanning	Economic Political/legal	Resource
Tofigh and Abedian [56]	National	Environmental scanning	Sociocultural Technological Economic Environmental Political/legal	Resource
Alizadeh et al. [14]	National	Environmental scanning	Technological Political/legal Sociocultural Economic	Resource
Chen and Wu [56]	Global Regional National	Environmental scanning	Economic	Resource
Wu and Chen [57]	Regional	Environmental scanning	Political/legal Economic	Resource
Abbaszadeh et al. [58]	National	Environmental scanning	Political/legal Economic Sociocultural	Resource
Mollahosseini et al. [59]	National	Environmental scanning	Environment	Resource
Achinas et al. [51]	Regional	Environmental scanning	Sociocultural Technological Economic Environmental Political/legal	

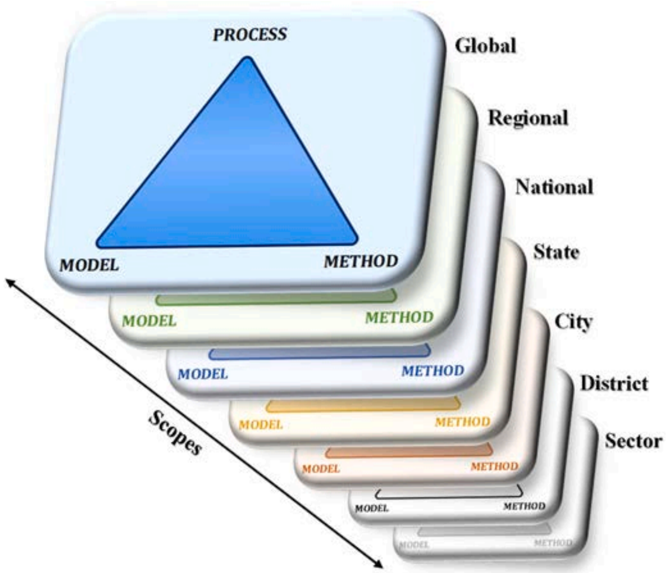

Fig. 8. An overview of the adopted concept.

the strategic management framework and to find more concrete methodology. The fifth stage is analysing and classifying the collected components. This activity provides a literature analysis by mapping the components to the specific aspects that need to be considered in strategic management methodology including scope, process, and model, as given in Table 2. Further explanation of this activity is given in Section 4.1.

The sixth stage is the identification of specific components that are related to the present study from the related concepts that are used in the existing study. This process assists the study in finding the knowledge gaps and identifying a new variable or scope in the study. The identified components are then integrated into a unified framework that can be seen in Figs. 9–23.

4. Development of the framework

This section presents the development process of the strategic management for global energy framework. It involves several stages of literature analysis consisting of a review of the related studies to analyse the adopted concepts and formulate the structure of the framework. The detailed procedure of this stage is described in the following subsections.

4.1. Concept analysis

The present study analyses the previous studies in the field of strategic management for energy to find an idea for formulating the framework. The literature analysis revealed four strategic management main aspects that need to be considered in the framework, including scope, process, model, and methodology.

The scope includes global, regional, national, state, city, district, and sector. It shows the level of stakeholders' involvement in all processes of strategic management. The process consists of analysis, strategy formulation, implementation, and evaluation and control. It shows how the stakeholders at a different level should act through all the process. In the global energy management, the analysis should be conducted within the boundary of global, region, country, state, city, district, and sector to determine vision and mission and set of objectives of each sector.

The model includes the I/O model and the resource-based model. The strategic management model shows the approach that needs to be envisaged throughout all strategic management processes. The I/O model embraces the external perspective that has a dominant influence on the strategic decisions for global energy management. The resource-based model adopts an internal perspective to enlighten distinctive internal resources, capabilities, and core competencies that serve as a source for getting above-average returns. According to this model, the resources, capabilities, and core competencies found in the internal environment are essential to determine the suitability of strategic actions. The methodology aspect shows a systematic procedure for investigating the strategic management process. These main aspects (scope, process, model, and methodology) are then integrated into a unified form, as shown in Fig. 8.

The next step in the development process is the collection of the strategic management scope, process, model, and methodology from the previous literature. Based on the literature analysis, the majority of study considered all main aspects. However, they do not consider all segments and elements of the aspects. For example, Jonsson et al. [52] focused their environmental scans related to regional energy security. They analysed the current energy security scenario based on political/legal, sociocultural, economic, technological, and environmental aspects. Terrados et al. [54] studied the development of renewable energy in the Spanish region and introduced a methodology for formulating strategies. They also investigated the planning of renewable energy based on several aspects, including technological, environment, socio-culture, and economy. The collected scope, process, model, and methodology from the previous studies are then classified, as given in Table 2.

4.2. Framework design

The strategic management framework for global energy is generally developed based on four main aspects, namely, scope, process, model, and method. These aspects are integrated and interconnected into a cohesive framework to provide a practical methodology for practitioners to design strategies for global energy. The framework consists of two parts: the main framework and the detailed framework. The main framework, as given in Fig. 9, provides an overall view of a methodology to design strategies for global energy. It includes the two main aspects, including scope and process. The remain aspects, model and method, are included in the detailed framework.

For the scope, the present study uses geographical levels of energy planning introduced by Prasad et al. [13]. This scope includes global, regional, national, state, city, district, and sector. This means that the

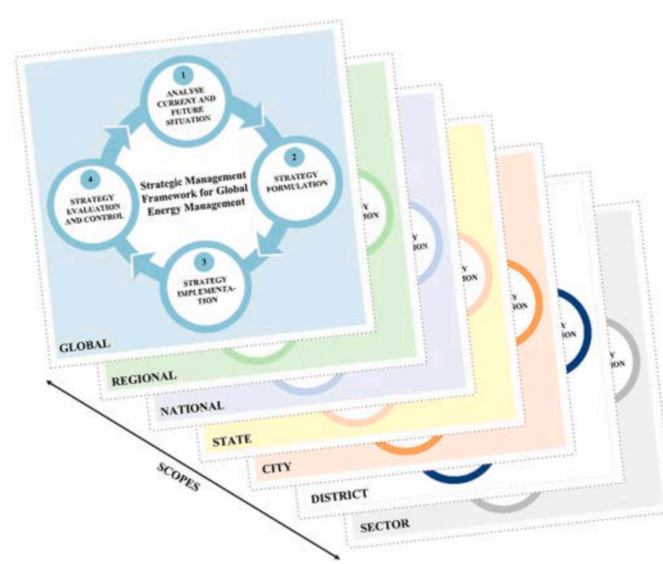

Fig. 9. The main strategic management framework for global energy.

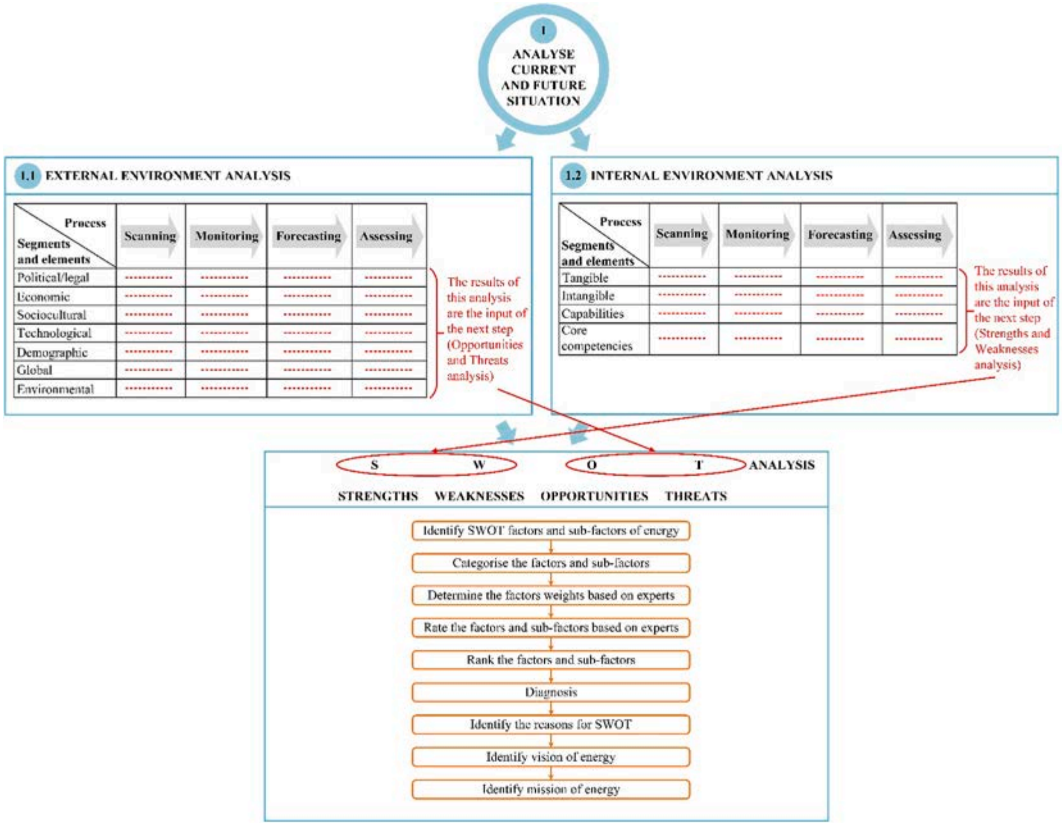

Fig. 10. The detailed framework – Analyse current and future situation.

1.1 EXTERNAL ENVIRONMENT ANALYSIS

PESTDGE Analysis:

1. **Political/legal segment:** antitrust laws, taxation laws, deregulation philosophies, labour training laws, educational philosophies and policies
2. **Economic segment:** inflation rates; interest rates; trade deficits or surpluses; budget deficits or surpluses; personal savings rate; business saving rates; gross domestic product; energy use per capita; energy use per unit of gross domestic product (GDP); efficiency of energy conversion and distribution; reserves-to-production ratio; resources-to-production ratio; industrial energy intensities; agricultural energy intensities; service/commercial energy intensities; household energy intensities; transport energy intensities; fuel shares in energy and electricity; non-carbon energy share in energy and electricity; renewable energy share in energy and electricity; end-use energy prices by fuel and by sector; net energy import dependency; stocks of critical fuels per corresponding fuel consumption
3. **Sociocultural segment:** women in the workforce; workforce diversity; attitudes about the quality of work life; concerns about the environment; shifts in work and career preferences; shifts in preferences regarding product and service characteristics; share of households (or population); share of household income spent for energy; household energy use; accident fatalities per energy produced
4. **Technological segment:** product innovations; applications of knowledge; focus of private and government supported research and development expenditures; new communication technologies
5. **Demographic segment:** population size; age structure; geographic distribution; ethnic mix; income distribution
6. **Global segment:** important political events; critical global markets; newly industrialised countries; different cultural and institutional attributes
7. **Environmental segment:** greenhouse gas (GHG) emissions from energy production and use; per capita and per unit of GDP; ambient concentrations of air pollutants in urban areas; air pollutant emissions for energy systems; contaminant discharges in liquid effluents from energy systems; oil discharges into coastal waters; soil area where acidification exceeds critical load; rate of deforestation attributed to energy use; ratio of solid waste generation to units of energy produced; ratio of solid waste properly disposed of to total generated solid waste; ratio of solid radioactive waste to units of energy produced; ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste

Fig. 11. Segments and elements of external environment analysis.

strategy for managing energy should be designed in every scope (top to down) so that all strategies are aligned and integrated. For the strategic management process, this study adopts the strategic management process from the work of Hitt et al. [36]. The process includes analyse current and future situation, strategy formulation, strategy implementation, and strategy evaluation and control. It is an iterative process as strategies should be constantly reviewed and updated every few years to continuously track energy performance. This process is useful to respond and react to rapidly changing global business environment and global issues.

As seen in Fig. 9, the strategic management process is similar in each scope. However, the strategies designed as an output of the process will be different as each scope has its own competencies and capabilities in managing energy strategies. It should be noted that the strategies designed in all areas should be perfectly aligned with the vision, mission, and goals of the global management to ensure that daily actions and decisions in regional, national, state, city, district, and sector in line with the strategic direction in the global scope.

The structure of the main framework is then broken down into a more detailed framework based on the strategic management process to facilitate the practitioners in following each process and step to design a strategy. The detailed framework consists of 1) Analyse current and future situation, 2) Strategy formulation, 3) Strategy implementation and 4) Strategy evaluation and control, which are presented in Figs. 10, 13, 15 and 22.

The analysis process begins with external and internal environments. The primary purpose of analysing the external environment is to determine opportunities and threats in global energy management. The external environmental analysis process should be in various segments, including political/legal, economic, sociocultural, technological, demographic, and global which is adapted from the work of Hitt et al. [36], the environmental segment which is taken from Achinas et al. [51]. The main purpose of the analysing the internal environment is to identify the strengths to develop and weaknesses to control global energy management. This analysis should be carried out in several segments, including tangible analysis, intangible analysis, capabilities, and core competencies, which are adapted from Hitt et al. [36].

The external and internal analysis activity can be carried out simultaneously. The segments of external and internal analysis are then detailed into several elements to show the specific criteria that need to be analysed. These elements are adopted from Hitt et al. [36] and IAEA [65] and they are consecutively presented in Figs. 11 and 12.

The next step of the analysis process is SWOT analysis by identifying the SWOT factors and sub-factors. SWOT is a technique to analyse the strengths, weaknesses, opportunities, and threats, then determine the strategies for global energy. As shown in Fig. 10, the output of internal environment analysis will be the input of strengths and weaknesses analysis; meanwhile, the output of external analysis will be the input of opportunities and threats analysis. The steps in SWOT analysis are altered from the work of Ervural et al. [55].

Strategy formulation, also known as strategic planning, is a process of developing the global energy strategy. In this process, the

Fig. 12. Segments and elements of the internal environment analysis.

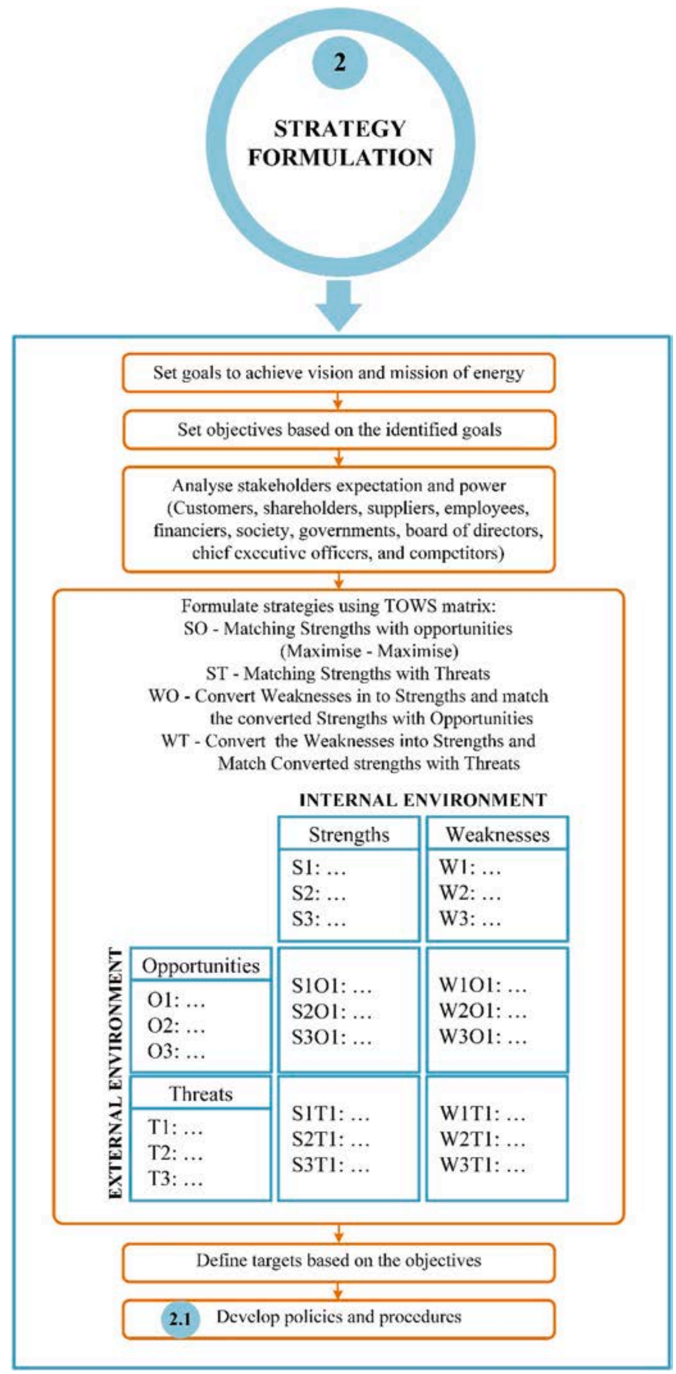

Fig. 13. Strategic management framework – Strategy formulation.

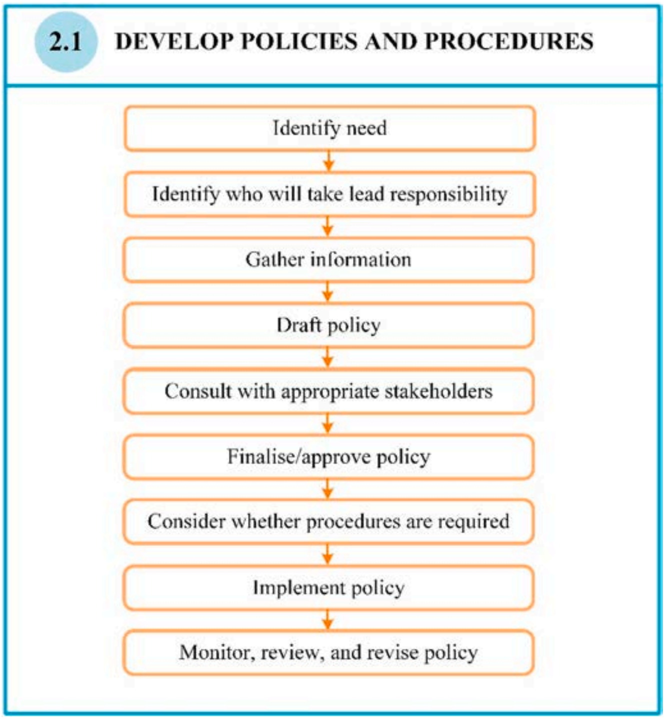

Fig. 14. Steps to develop policies and procedures.

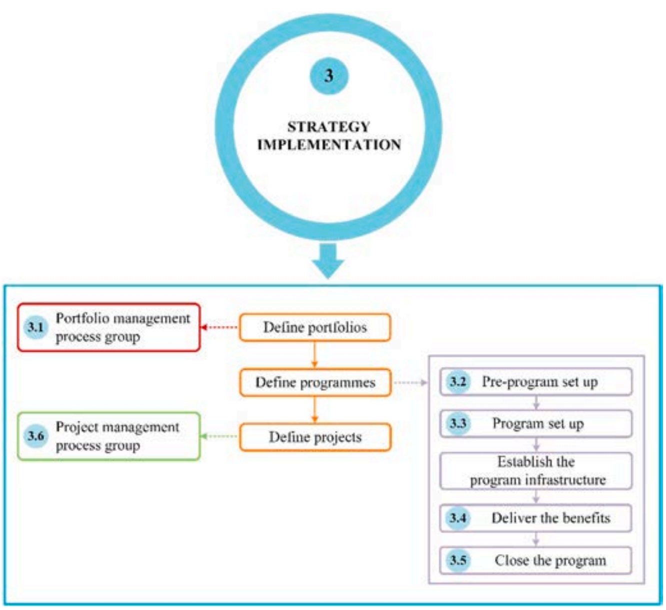

Fig. 15. Strategic management framework – Strategy implementation.

practitioners should identify and decide the most appropriate courses of action to achieve the goals of global energy implementation. It is the primary process in strategic management as it provides an action plan that leads to the expected outcomes.

Strategy formulation requires the policymakers to define the strategic goals and objectives to achieve the identified vision and mission [41]. Then, stakeholder expectations and power, production, market share, and advanced technology should be analysed to discover and align their expectations and individual impact on the product [46]. This study adopts stakeholders expectation analysis step from Li et al. [66], who investigated energy performance from various stakeholders. The formulation of strategy generally uses the TOWS matrix as a tool for analysing, generating, comparing and selecting the most appropriate strategy to achieve the goals of global energy implementation. The proposed strategic management framework used a TOWS matrix from Gottfried et al. [67]. The next step is defining the performance targets and policies. Fig. 13 presents the detailed process in strategy formulation.

The study details the development of policies and procedures, as provided in Fig. 14. The development of policies aims to confirm obedience with laws and regulations, provide direction for decision-making, and streamline internal processes. This activity begins with the identification of needs by assessing the activities, responsibilities, and external environment. Then, the management committee needs to identify who will be responsible for the policy based on the required expertise. Some information related to legal responsibility, the accuracy

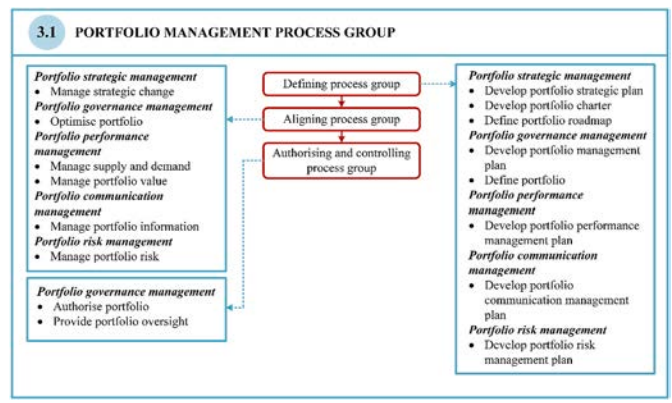

Fig. 16. Portfolio management process group.

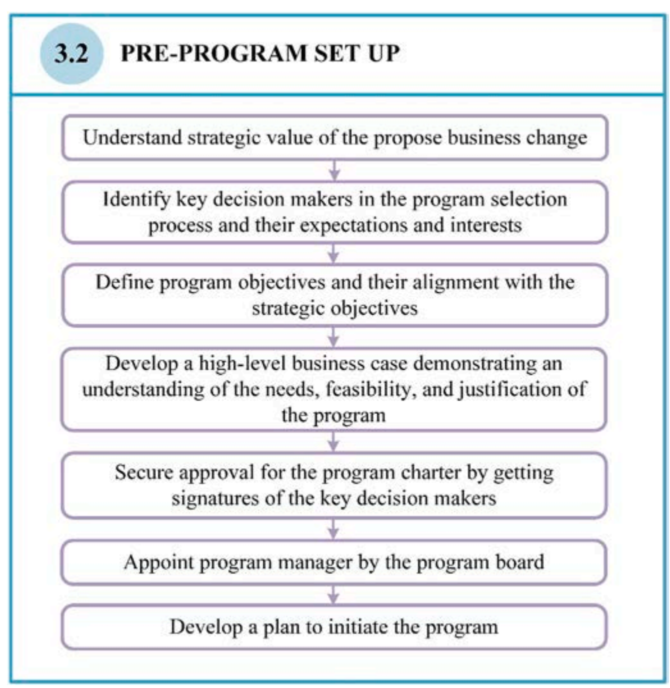

Fig. 17. Steps to pre-program set up.

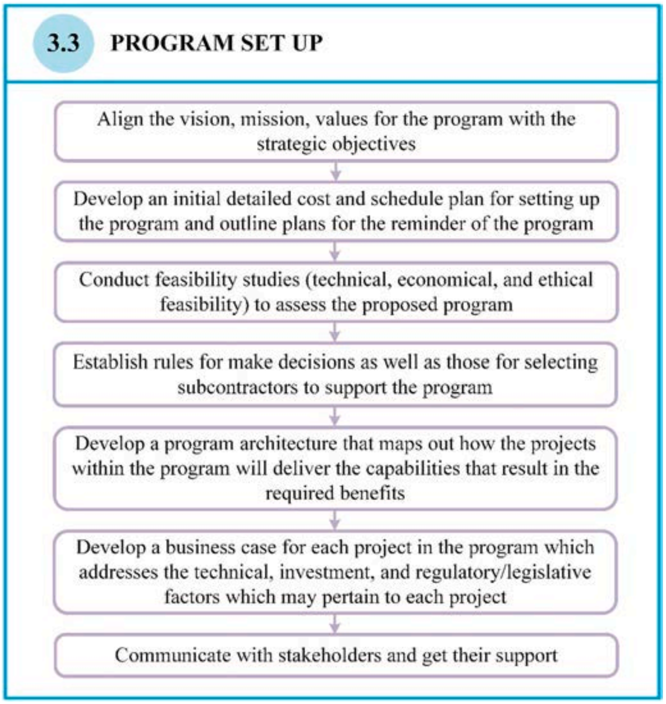

Fig. 18. Steps to the program set up.

of the data and information, competitors, and the availability of the existing guidelines needs to be gathered to support the planning. The next step is the draft policy and ensures that the designed policy are appropriate to the stakeholder's expectation as they need to approve it. After the approval, the developed policies and procedures are implemented, monitored, and reviewed. Policy revision is required to up-to-date the information related to regulations, technology, and best practices, and to make policies consistent and effective.

The next strategic management process is strategy implementation that requires the practitioners to execute and manage strategic activities associated with the delivery of the strategic plan. The strategy implementation process involves the policymakers to develop and integrate business structure, culture, resources, and control system of global energy following the identified strategies [43]. Fig. 15 illustrates the elements of strategy implementation.

Strategy implementation involves three main activities: defining portfolios, programmes and projects. A portfolio is a group of programs and projects to facilitate effective management to attain strategic business objectives. A program is a collection of several projects that are managed and delivered as a single package. A project is a series of activities that need to be accomplished to achieve a specific outcome. Defining portfolios, programmes, and projects are required in the strategy implementation process to have a concrete, detailed, and comprehensive implementation plan that supports the success of strategic management.

Portfolio management process group can be used to define the portfolios. This study adopts the detailed process from The Standard for Program Management [68], as it is a formal standard used for managing portfolios. The portfolio management process group entails three main steps, including defining, aligning, and authorising and controlling process group. The activities under each step are mapped to five portfolio knowledge areas: strategic management, governance management, performance management, communication management, and risk management. Fig. 16 demonstrates the detailed steps of the portfolio management process group.

As mentioned in The Standard for Program Management [68], the process of defining programmes consists of several steps including pre-program setup, program set up, establish program management and technical infrastructure, deliver the benefits, and closing. The objective of the pre-program set-up is to establish program support and approval from the key decision-makers. The detailed steps in the pre-program set up are illustrated in Fig. 17. After the program has been approved, the program team needs to set up the program by developing a detailed roadmap that provides direction in managing the program and defining its key deliverables. Fig. 18 shows the detailed steps of the program set-up.

The next activity is to establish an infrastructure to support the

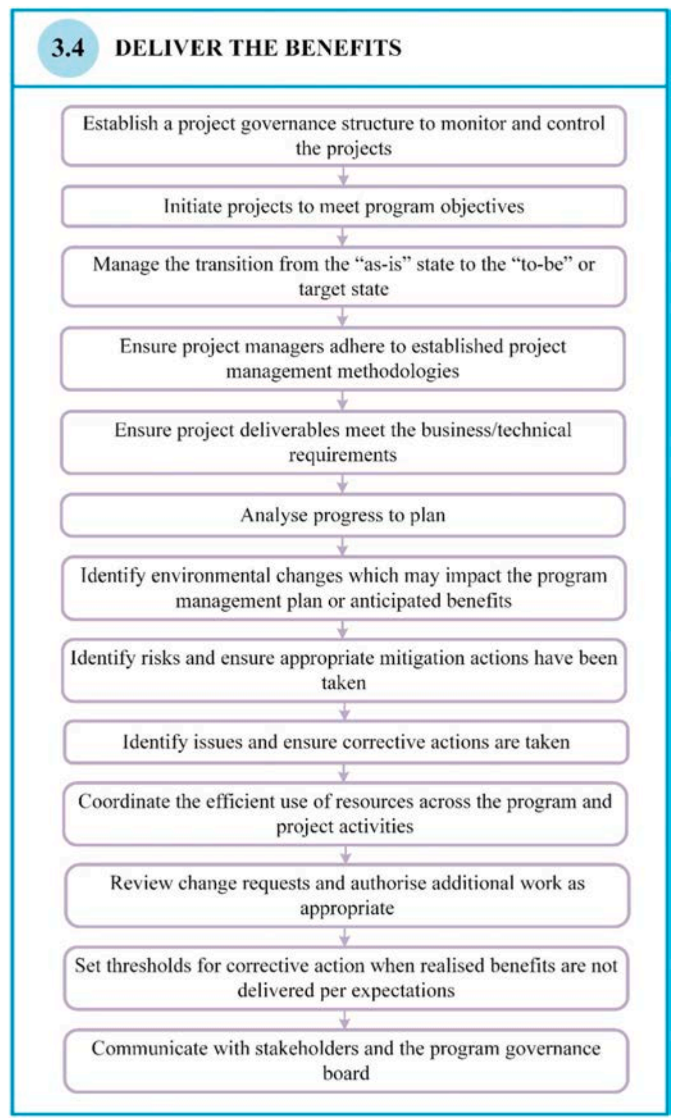

Fig. 19. Steps to deliver the benefits.

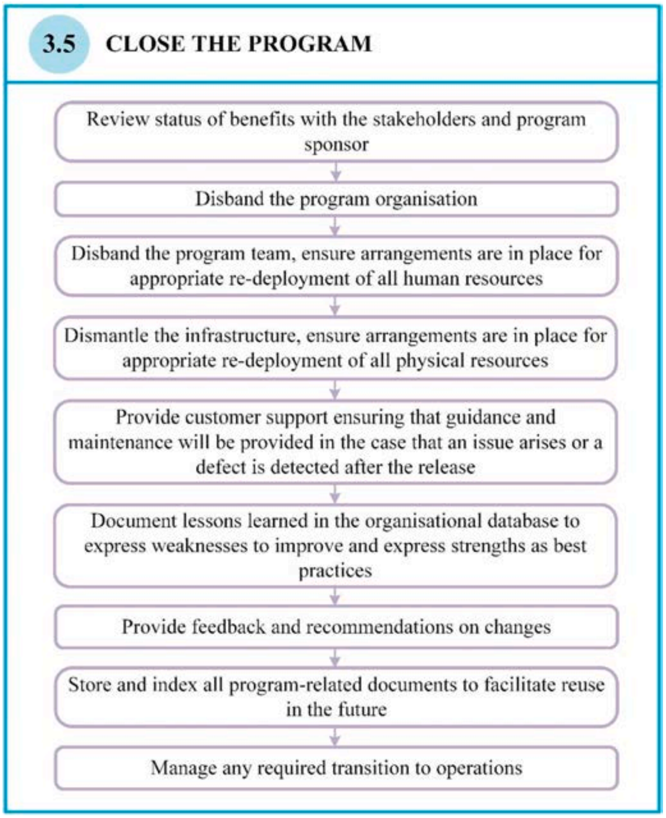

Fig. 20. Steps to close the program.

implementation of the program and its constituent projects. This infrastructure includes processes and procedures, specific tools (software and hardware), and facilities. Establish the program infrastructure is a key success to support the success of program execution. Delivering the incremental benefits of a program is a process to review the program and its constituent projects, whether they have achieved the planned benefits or not. The results should be communicated to the stakeholders and key decision-makers for their feedbacks. The detailed steps of this process can be seen in Fig. 19.

The final step in defining programmes is closing that entails shut down the process of the program organisation and infrastructure. The program management team needs to ensure that the closure is smooth and safe. As an outcome, the team needs to document lessons learned for future works, and recommendations on changes that may benefit the stakeholders. Fig. 20 is given to describe the specific steps in the program closure.

This study adopts the steps to define projects from the Project Management Body of Knowledge [69]. The steps consist of initiating, planning, executing, monitoring/controlling, and closing. The detailed activities under each step are categorised based on ten project management knowledge areas including integration, scope, schedule, cost, quality, resource, communications, risk, procurement, and stakeholder. All the steps and activities can be seen in Fig. 21.

The final strategic management process is an evaluation and control of strategies where policymakers need to ensure that the strategy formulated are adequately implemented and fulfil the objectives or not [70]. Implementing strategies requires effective control and information systems, which provide practitioners with accurate, complete, real-time feedback so they can make decisions based on data [71]. Fig. 22 shows the detailed process of strategy evaluation and control. This study adopts the intricate process of strategy evaluation and control from the work of Wheelen and Hunger [72]. This process helps policymakers to monitor the progress of strategy implementation. Adequate and timely feedback is the basis for an effective strategy. In this process, the practitioners can ascertain what needs to be achieved by comparing the performance with the desired results and providing the feedback to evaluate the results and take corrective actions as required.

5. Results discussion

The strategic management framework for global energy is generally developed to guide policymakers in designing energy strategies to achieve a sustainable strategic competition in the worldwide market. It is an essential tool for policymakers such as intergovernmental organisations and government agencies to formulate and implement the goals and initiatives involved in the energy strategies. An energy strategy has to exist to support the business functions and operations in creating a wise decision-making process.

The strategic management framework entails an evaluation of the energy business vision, goals, objectives, and plans for the future. The framework also can be useful for energy producers, suppliers, and customers (international institutions, national government, equipment manufacturers and retailers, energy supply companies, facilities management companies, energy services companies, and energy producers) to grasp the essential aspects in developing energy strategies in the international and national scope. Fig. 23 provides an overview of the framework in the form of a sequential diagram. The policymakers can apply the framework by sequentially following the process and steps in the framework.

The economic crisis caused by the COVID-19 pandemic is prompting international and national governments around the world to enact emergency support measures. Economic activity and the wellbeing of households during the crisis has served to underline the urgency of achieving universal access to energy.

The COVID-19 also increased the demand for PPE (Personal Protection Equipment) very considerably [73]. During the outbreak of the pandemics the generation of medical waste increased sharply (+370%) in just Hubei Province, with a high proportion of plastics. In spring worldwide were needed 129 G masks/month, consuming 1.29 TWh/month = ~4.6 PJ/month [74]. The growth rate of medical-use ethanol in 2020 was so far 20.0% and has been still growing. For example, in March 2020, sales of multipurpose cleaners in the USA spiked by 166% and aerosol disinfectants 343% from a year ago, which disrupted the supply chains of disinfectants [75].

The energy sector has played a vital role in supporting the delivery of healthcare, remote working, and many other needs. Like many other sectors, however, the energy sector has been strongly affected by the COVID-19 crisis [76]. In these circumstances, policymakers need to review and rethink their energy strategy and long-term plans to address the problems posed by pandemics and survive during and after a pandemic. The proposed strategic management framework would help them to re-analyse the strategies and actions requiring changes to attain better performance and competitive advantage.

In providing long-term recovery plans, the policymakers need to reassess several energy sector measures, which generally consist of electricity, transport, industry, buildings, fuel supply, and strategic opportunities in technology innovation [77]. They has to look at the short-term and long-term implications of these measures for job creation, economic growth, energy security, resilience, and emissions. Some

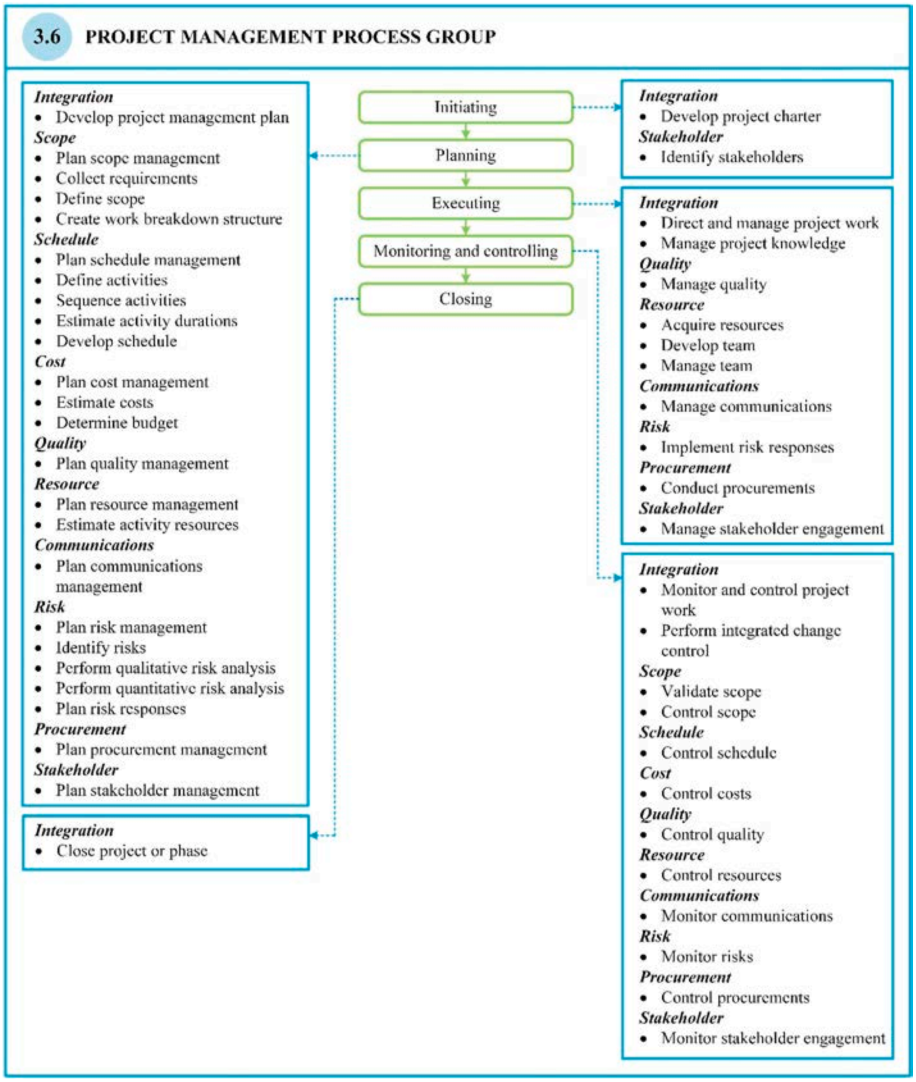

Fig. 21. Project management process group.

measures may be more appropriate for certain countries depending on national circumstances. Suppose governments around the world align their strategies and actions, there may be synergistic benefits from more integrated energy value chains and reduced costs related to cumulative adoption and policy coordination across markets. Such coordination can make for a more cost-effective and quicker recovery for all.

Three aspects of the strategic energy plan requiring revision in light of the COVID-19 crisis may include, but not limited to customers' energy needs, demands, and the competitive positioning, marketing strategies, and supply and operations. The policymakers need to re-analyse and update current and future situation, which involves internal and external analysis, as seen in Fig. 10. They need to go through all the strategic management process and update the related energy strategies and actions.

This study proposes a strategic management framework and provides a detailed process for formulating energy strategies. The process in the framework looks general, which means that it can be used in another sector besides energy. However, the identified elements in the framework are more specific to the energy sector. For instance, the segments of external environment analysis that consider the amounts of energy production and use.

The proposed strategic management framework provides a holistic methodology for formulating and managing energy strategies. The results of this study differ from previous studies as the resulting framework integrates all important concepts that need to be considered in the process of energy strategy formulation and management. In contrast, previous studies are only specific to one perspective in strategic management, such as scanning process or scenario planning. Therefore, the present study gives fresh insights into the strategic management field, particularly in the energy sector. In connection with the COVID-19 pandemic which affects the performance of the energy sector, the proposed framework would facilitate the policymakers to focus on which segments that are crucial to change according to the results of internal and external environment analysis.

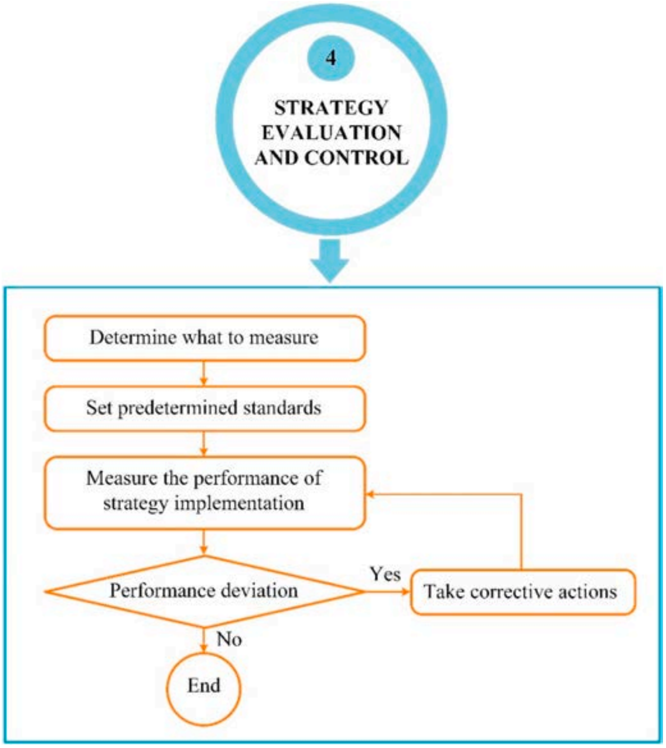

Fig. 22. Strategic management framework – Strategy evaluation and control.

method. The detail segments and elements of each aspect were identified according to several concepts in strategic management and energy planning. This study provides several contributions for academics and practitioners. For academics, this research will advance the development of research in the field of strategic management for global energy. The framework developed is proposed to address the existing research gaps in this field. For practitioners, the proposed methodology can be adopted by policymakers at the global, regional, national, state, city, districts, and sectors, such as intergovernmental organisations and government agencies, as a guide for analysing, formulating, implementing, and evaluating energy strategies globally. The policymakers can follow the actions and decisions that help them to achieve their goals. The method would minimise the effects of adversative conditions and changes.

A study that analyses current global energy based on the identified segments and elements of the framework would be valuable for practitioners—for instance, scanning global energy from an economic, political, sociocultural, demographic, technological, global, or environmental perspective. This study would give a detailed overview of the general environment analysis of the current condition in global energy. This analysis is an important step in strategic management by providing possible threats and opportunities in global energy implementation. Another potential research is a study that analyses internal environments such as tangible and intangible resources, capabilities, or core competencies of worldwide energy implementation. This study is essential to show the existing threats that can hinder the implementation and opportunities from advancing global energy implementation.

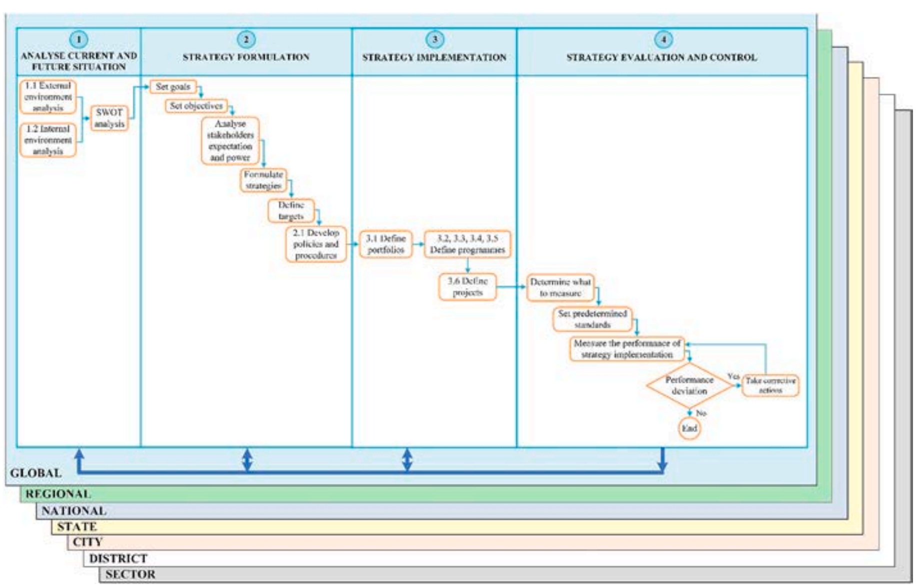

Fig. 23. An overview of the strategic management framework.

6. Conclusions

Policymakers at the global and national levels require an appropriate strategic management method to manage global energy. This method should integrate relevant aspects of strategic management into a unified form and provide sequential stages of how to develop global energy strategic management. Based on these ideas, a strategic management framework for global energy is developed. This framework would help practitioners to provide detailed structure and process for developing global energy strategies.

The strategic management framework was structured based on four aspects, including scope, strategic management process, model, and

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Repeated leak detection and repair surveys reduce methane emissions over scale of years

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Abstract

Reducing methane emissions from the oil and gas industry is a critical climate action policy tool in Canada and the US. Optical gas imaging-based leak detection and repair (LDAR) surveys are commonly used to address fugitive methane emissions or leaks. Despite widespread use, there is little empirical measurement of the effectiveness of LDAR programs at reducing long-term leakage, especially over the scale of months to years. In this study, we measure the effectiveness of LDAR surveys by quantifying emissions at 36 unconventional liquids-rich natural gas facilities in Alberta, Canada. A representative subset of these 36 facilities were visited twice by the same detection team: an initial survey and a post-repair re-survey occurring ~0.5–2 years after the initial survey. Overall, total emissions reduced by 44% after one LDAR survey, combining a reduction in fugitive emissions of 22% and vented emissions by 47%. Furthermore, >90% of the leaks found in the initial survey were not emitting in the re-survey, suggesting high repair effectiveness. However, fugitive emissions reduced by only 22% because of new leaks that occurred between the surveys. This indicates a need for frequent, effective, and low-cost LDAR surveys to target new leaks. The large reduction in vent emissions is associated with potentially stochastic changes to tank-related emissions, which contributed ~45% of all emissions. Our data suggest a key role for tank-specific abatement strategies as an effective way to reduce oil and gas methane emissions. Finally, mitigation policies will also benefit from more definitive classification of leaks and vents.

Introduction

Methane emissions from the oil and gas industry are the largest anthropogenic source of methane in Canada, accounting for over 40% of total emissions in 2017 [1, p 3]. With methane having a global warming potential (GWP) significantly higher than carbon dioxide (CO_2), mitigating methane emissions is critical to achieve the Paris climate targets [2]. Furthermore, given the short atmospheric lifetime of methane, reducing emissions will result in an immediate reduction in radiative forcing. The sustainability of the natural gas industry, particularly considering growing liquefied natural gas (LNG) exports, will be further improved by reducing fugitive and vented methane emissions. Fugitive emissions or leaks refer to unintentional releases of methane, while vents refer to international releases. Finally, addressing methane emissions also reduces emissions of volatile organic compounds from oil and gas operations, improving local air quality [3, 4].

Recent research on the discrepancy between official inventory estimates and measurements of methane emissions have raised concerns about the need for more effective methane regulations. Both ground-based and aerial-measurements in Alberta showed higher vented and total methane emissions compared to provincial regulatory estimates [5, 6]. Similarly, mobile measurements using truck-mounted sensor systems in British Columbia and Alberta have consistently shown that a majority of the emissions are dominated by a small number of high-emitting sites, often identified as 'super-emitters' [5, 7, 8]. This is not unique to oil and gas activity in Canada—measurements of methane emissions across different shale basins in the US demonstrate evidence of super-emitters, widespread underestimation compared to US EPA inventory, and significant spatial and temporal variability [9–12].

Recently, governments in the US and Canada have developed policies to reduce methane emissions from the oil and gas industry [13, 14]. These policies typically include a combination of absolute limits on venting and periodic leak detection and repair (LDAR) programs to detect and mitigate fugitive emissions or leaks [15, 16]. While many technologies have been recently developed to detect methane emissions, most regulatory LDAR programs require the use of optical gas imaging (OGI) systems for leak detection [17–19]. While OGI-based LDAR programs have been found to be effective in a survey of operators, there has been no systematic study of the effectiveness of repair process and the persistence of emissions reductions from one survey to the next in real-world operating conditions [20]. One recent study sought to understand the time evolution of emissions through year on year aerial OGI-based surveys, although it did not involve any intervening repair process [21].

In this work, we take the novel (to our knowledge) step to determine the effectiveness of LDAR programs by performing repeated detailed ground surveys at facilities using consistent measurement and tracking techniques over the course of 0.5–2 years. By completing two OGI-based LDAR surveys at well-pads and processing plants, an initial survey followed by a post-repair re-survey, we find that the repair process is highly effective—over 90% of leaks fixed after the initial survey do not re-appear. Our study identifies important dynamics underlying methane emissions at upstream production facilities that can help regulators develop targeted policies within the context of LDAR programs.

Methods

Leak detection and repair surveys

All LDAR surveys in this study were conducted by Davis Safety Consulting Ltd with personnel trained and certified in FLIR-camera based leak detection and thermography technologies. It was critical to have a trained and experienced crew perform the LDAR surveys because recent studies of survey crews showed that consistent leak detection results are achieved only when crews have experience conducting around 400 prior surveys [22]. All surveys were performed at facilities operated by Seven Generations Energy Ltd (henceforth 'the company') in the Montney basin in Northwest Alberta. Data collected as part of this study is publicly available through the Harvard dataverse repository and the supplementary material is available online at stacks.iop.org/ERL/15/034029/mmedia section [23].

The site-survey took place in two stages. In the first stage, a thermographer examines every component and equipment on site using a FLIR GF-320 infrared camera. A second crew member records details of each leak (location, type of leak, and other relevant parameters) electronically, and physically attaches a unique tag to the leaking component for identification. The facility manager is immediately notified of leaks that pose risk to life or property. In the second stage, leaks with tags have their volumetric flow rate quantified using a Bacharach Hi-Flow sampler. Leaks that are either inaccessible or pose safety concerns are not quantified—in this study emission rates from these leaks were estimated using literature values. Finally, the facility operator is supplied with reports that detail leak locations, quantified emission rates, as well as photos and videos of each leak. We do not get into the details of specific repairs undertaken by operators but only evaluate the changes to emissions in facilities that had undergone repairs. While such repair details—part replacement or maintenance—will affect the cost of the repair process, it is not material to the emissions reduction efficacy of LDAR programs.

The detection limit of FLIR technologies varies with weather conditions, temperature of the equipment, operator experience, and imaging distance [19, 24]. To account for daily changes in weather, the FLIR camera is qualitatively verified every day before starting the survey using a propane standard at a flow rate of 50–60 g h^{-1} from a ¼ inch orifice, with a background at ambient temperature (e.g. equipment or a wall). The distance at which this 'standard leak' is observed is set as the maximum imaging distance for that day. This calibration procedure aims to reduce variability in the detection limit of the camera with changing weather conditions, and to ensure that data across multiple days are more comparable. Hourly changes in weather are not as important if the general outlook for the day (sunny, partially cloudy, etc) remains consistent [24].

Initial survey

The LDAR surveys were conducted every quarter in 2016 and 2017, such that all major facilities in the company's operating assets were surveyed once per year. Initial surveys covered 36 sites which consisted of 30 well pads and 6 processing plants. The 30 well pads consisted of 10 super-pads, 7 satellite pads, and 13 single well-sites. Super pads, which serve as gathering points for production from smaller satellite pads, also have limited processing equipment such as separators and dehydrators on site. Survey speed varied by the size of facilities: in one day (~10 h), about 4–6 satellite well-pads can be surveyed while larger super-pads and processing plants could take up to three days. The results of the LDAR survey from each of these sites were provided to the site manager within two weeks of the survey, with the expectation that re-survey may occur to evaluate the effectiveness of repair. Daily and monthly average production data were obtained from the company for all sites in order to calculate proportional loss rates. A total of 969 leaks and 686 vents were found in initial surveys, of which ~70% were directly quantified.

Re-survey

To check the effectiveness of repair procedures, 8 representative sites from the initial survey were chosen by the science team (APR, DRS, and ARB) to be re-surveyed using identical procedures described above. These sites were visited 6–13 months after the initial survey. The site managers at these sites were not informed *a priori* about the arrival of the survey crew to avoid last-minute interventions to reduce leakage. Post-survey, we worked with site managers to catalog all equipment or well changes that occurred at a site since the initial survey. This is critical to directly compare pre- and post-LDAR emissions at these sites and remove the influence of new equipment added between the two surveys as much as possible. A total of 130 leaks and 135 vents were found during the 8 re-survey site visits, of which 72% were directly quantified.

Emissions accounting (post-survey analysis)

Not all emissions detected by the OGI crew could be quantified by the Hi-Flow sampler because of access or safety issues. In order to develop a complete picture of site-level emissions based on bottom-up component-level surveys, we supplemented the non-quantified emissions using flow rate estimates based on the empirical LDAR dataset or literature surveys. For those component-types where partial measurements were available (see S.I. data spreadsheet), we assigned the average quantified emission rate for that component-type to the non-quantified emission sources, specific to each site-type. This method of using leak emissions factors is standard practice in methane emissions accounting. We only used data from the initial LDAR surveys to calculate emissions factors to better represent native emission rates pre-repair.

Tank emissions estimate

One type of emission—tank thief hatch and tank pressure release valve—lacked any quantification measurements in our study. This is because quantification using the Hi-Flow sampler cannot be used on tanks due to accessibility and safety issues. Assuming zero emissions from tanks because they were not quantified will lead to significant underestimation of emissions and introduce bias in the data. To solve this challenge, we develop custom emissions factors for tank-related emissions using data available from multiple peer-reviewed studies. First, we compiled a database of all peer-reviewed tank-related emissions measurements in the literature, disaggregated by site-type (e.g. well pads, processing plant, compressor station) and component (thief hatch, level controller, etc) [25–31]. Second, we develop emissions factors for tank emissions using this database for each site type—tanks on well-pads emit, on average, 30 kg CH_4/d, while those at processing plants emit 89 kg CH_4/d. These averages are used to estimate contribution of tanks to total site-level emissions. Third, we use non-parametric bootstrapping methods to estimate confidence intervals on tank emissions in this study, disaggregated by site type.

Throughout this study, measured volume flow rates have been converted to CH_4 mass flow rates assuming an average CH_4 mole fraction of 80.8% in the gas stream. This value represents the average methane composition at the company metering station, which receives gas from upstream well pads.

Results and discussion

Initial survey

Figure 1 shows the cumulative fraction of total emissions as a function of rank-ordered emitters at the component and site-level aggregation in the initial LDAR survey of 36 sites. As seen in many recent bottom-up studies of methane emission, we find that component-level emissions exhibit a highly skewed leak-size distribution—the top 5% of emitters contribute ~51% of total emissions [9]. Across all 36 sites in the initial survey, leaks and vents represented 15% and 85% of total emissions, respectively. There is no significant difference in the skewness of the size distributions of vents and leaks (see figure 1). The high fraction of emissions associated with vents is partly an artifact of classification—many jurisdictions in the US and Canada classify tank-related emissions as vents, even if the emission could be technically fixed (e.g. open thief hatch). If tanks do not contain a control

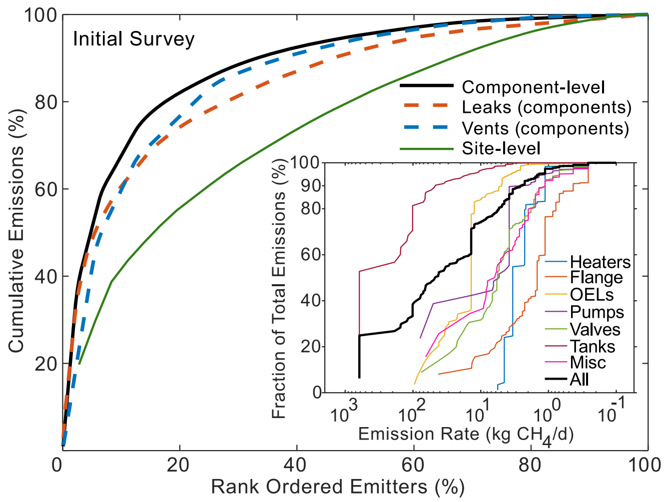

Figure 1. Component- and site-level emissions from initial LDAR survey of 36 sites. (Main) Rank-ordered component-level (black) and site-level (green) total methane emissions measured across 36 sites. The component-level emissions are further broken down into intentional emissions or vents (blue dashed line) and unintentional emissions or leaks (red dashed line). The largest 5% of emitters correspond to 51% and 30% of total emissions at the component-level and site-level, respectively. (Inset) Cumulative leak size distribution across different components in the initial survey—overall, 90% of the emissions (black line) are larger than about 3 kg CH_4/d. Note that the *x*-axis is displayed in descending order of emission rate.

equipment like a vapor recovery unit, tank-related emissions are classified as vents. Here, tank-related emissions contributed to 75% of all vented emissions, or 64% of total emissions. Of the total tank-related emissions, 78% or 949 kg CH_4/d can be attributed to emissions from level indicators, in line with recent findings that super-emitters are often caused by abnormal process conditions [32]. Tank-related emissions in this study are assigned by drawing from an empirical distribution of emissions from previously published studies (see Methods). Figure 1 also shows the cumulative fraction of emissions as a function of rank-ordered site-level data. Although less skewed than the component-level emission, the highest emitting top two facilities (5%, $n = 36$) contribute to 30% of total site-level emissions.

The inset of figure 1 shows the cumulative leak-size distribution as a function of emission rate disaggregated by major component types. Overall, 90% of emissions are from components emitting at least 3 kg CH_4 per day (kg CH_4/d), an order of magnitude smaller than a recent meta-analysis of methane emissions from US oil and gas operations [9]. However, the meta-analysis included emissions from compressor seals that are significantly larger than typical leaks. Excluding compressors, the 90% cut-off in the meta-analysis for leaks is about 4 kg CH_4/d, similar to results presented here. The mean and the median emission rates are 5.8 kg CH_4/d and 1.1 kg CH_4/d, respectively. However, there is significant variation across different component types—emissions from flanges exhibit some of the smallest rates, with a 90% cut-off at 0.6 kg CH_4/d, while tanks are the largest single emission source with a 90% cut-off at 25 kg CH_4/d. The mean emission rate from tank sources is 52 kg CH_4/d (95% C.I. [34, 89]), almost an order of magnitude larger than the overall mean emission rate across all components. The outsized role of tanks in contributing to overall methane emissions at natural gas facilities has been a defining feature in many recent studies, and points to a critical need for tank-focused LDAR regulations [31].

Figure 2(a) shows the site-level proportional loss rate as a function of gas production for 22 well-pads, calculated using the daily average production volume on the day of the initial LDAR survey. Only 22 of the 30 well pads are shown here because they were individually metered, allowing a proportional loss rate calculation. Using monthly average production volumes did not significantly alter the proportional loss rate. We find an inverse relationship between loss rates and production values in a log-log plot, with an R^2 coefficient of 0.82. Furthermore, separate data from satellite pads and super pads show that there may be emissions reductions advantages to aggregating production from many wells on larger pads. The average production normalized leakage rate for satellite pads and well sites is 0.21%, while that for super pads is 0.03%. These proportional loss rates are lower than many recent studies of methane emissions in Canada [6, 8].

Figure 2(b) shows the absolute methane leakage volumes as a function of production for the same set of sites in figure 2(a). There is only a weak inverse correlation between daily production volumes and emission rates compared to the proportional loss rate data.

While this only represents data from one specific operator, it speaks to recent debates over policy exception for low-producing wells [33]. Our data suggests that emission volumes are not proportional to production, and therefore regulations to limit methane emissions must consider both low- and high-producing wells. These findings reflect recent observations

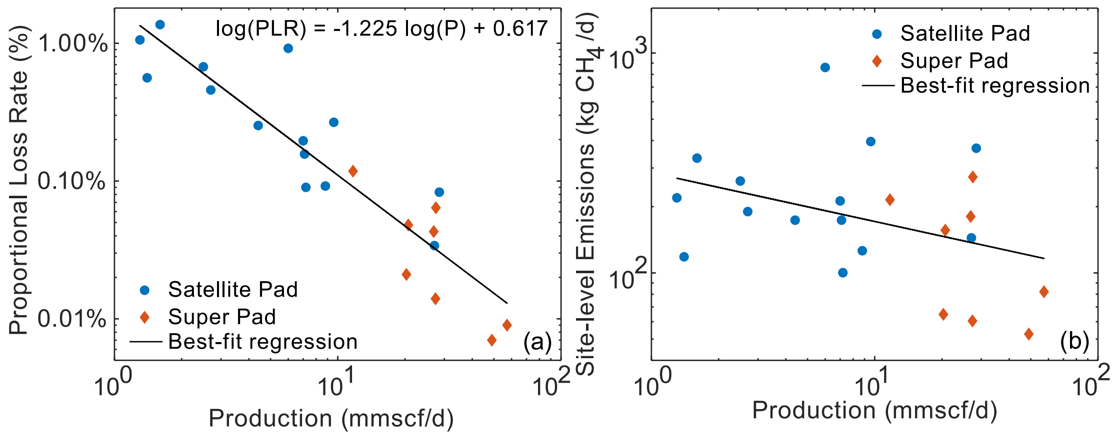

Figure 2. Proportional loss rate as a function of gas production. (a) Across 22 sites, we find that the proportional loss rate, calculated as the ratio of total methane leakage volume to total production volume, decreases as a function of increasing gas production—higher producing sites have comparatively lower fractional emissions. (b) Absolute site-level emissions as a function of production—emissions only weakly depend on production levels.

elsewhere–Omara *et al* also found that site-level proportional loss rate from low producing sites is higher than at high producing sites [34]. Future studies with larger sample sizes could help to establish the contribution of methane emissions from low producing wells.

The relatively low proportional loss rates reported here can be attributed to several factors. One, the loss rates calculated in this study are limited to pad-level emissions and do not include emissions from gathering and boosting stations. Two, the reported loss rates do not include methane slip from compressors or emissions from episodic events like liquids unloading which are typically not measured as part of LDAR surveys but have been shown to be a significant source of methane emissions in the literature [30, 35]. Three, the combination of newer equipment (all sites have been developed since 2014), a liquids-rich reservoir, and a sustainability-focused company operating practices result in lower emissions than is typically observed. For example, the company has a voluntary LDAR program to reduce methane emissions from its operations and uses instrument-air driven pneumatic systems instead of natural gas whenever feasible. Therefore, the low proportional loss rates observed here is likely not representative of all operators. This also indicates that it is possible for oil and gas operations to have leakage significantly lower than 1% even under a voluntary mitigation plan. Yet, evidence from many recent studies show methane emissions larger than reported or official inventory estimates [5, 6]. It suggests that there might be significant differences in methane emissions across operators—a hypothesis with major implications for emissions policy. Future studies should explore the impact of institutional practices on environmental outcomes.

Figure 3(a) shows normalized methane emissions at 8 selected facilities where a post-repair re-survey was conducted. The initial survey dates and emission rates for the 8 facilities, while occurring over a period of one year, has been normalized to start at time, $t = 0$. The post-repair survey date is scaled similarly. Because all operators were given the results from the initial survey and were informed of potential re-survey, we expect all 8 sites to have undergone some level of repair. In 2 of the 8 sites where re-surveys were conducted, additional equipment was installed between the initial and post-repair survey (site #2 and site #5). For this analysis, whenever possible, we removed those emissions associated with the newer equipment that were not present during the initial survey while calculating the post-repair re-survey emissions.

Overall, emissions reduced by 44% across all 8 facilities between the first and second LDAR survey. Incidentally, this emissions reduction is similar to US EPA and Environment and Climate Change Canada's (ECCC) modelling assumption that an annual OGI-based LDAR survey will reduce emissions by 40% [16]. 6 of the 8 sites re-surveyed saw average emissions reductions of 46% (304 to 165 kg CH_4/d/site), while 2 of the 8 sites (site #5 and site #8) saw emissions increase by an average of 52% (37 to 57 kg CH_4/d/site). The emissions increase on site #5 could be due to uncertainty associated with attributing emissions to only part of the site that was not expanded between the two surveys. The overall emission reductions of 44% between initial survey and post-repair re-survey is a combination of an average *decrease* in leaks of 22% (274 to 214 kg CH_4/d) and vents of 47% (1625 to 888 kg CH_4/d). In the initial survey at our 8 sites, leaks and vents contributed to about 15% and 85% of total emissions, respectively. This is similar to leak-vent split observed in the overall population ($n = 36$), the skewness being an artifact of classifying tank-related emissions as vents (see figure 1). In the post-repair re-survey, leak and vents contributed to 19% and 81% of total emissions, respectively. Figure 3(b) shows the absolute emissions levels at the 8 sites where a post-repair re-survey was conducted in log-scale. The initial

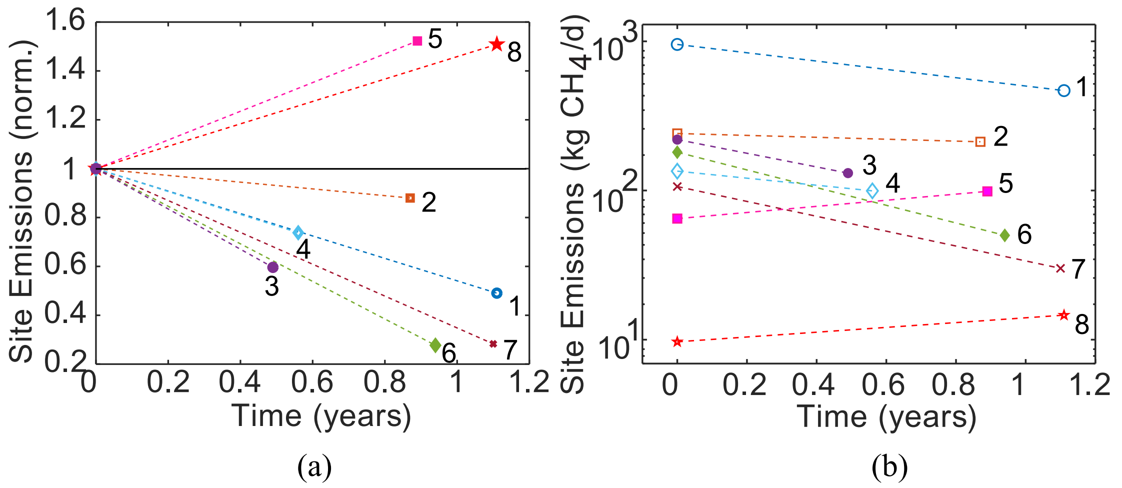

Figure 3. Effectiveness of repair using pre- and post-LDAR surveys. (a) Normalized, and (b) absolute site-level methane emissions during initial survey (pre-repair, $t = 0$) across 8 different sites and post-repair LDAR survey ($t \geqslant 0.5$ years). 6 out of the 8 sites show a reduction in emissions in the second survey, suggesting that LDAR surveys are effective in reducing emissions. The average emission reduction across the 6 sites was 44% after one LDAR survey.

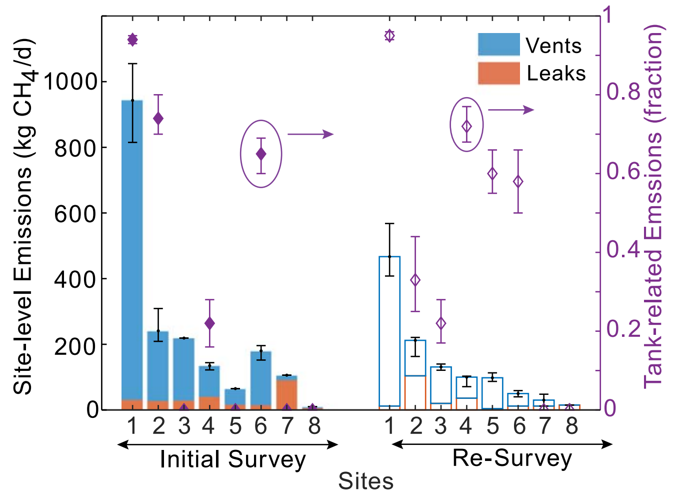

Figure 4. Site-level analysis of temporal changes in methane emissions. Site-level emissions broken down into leaks (red) and vents (blue) during the initial and final survey for the 8 sites shown in figure 3. Leaks and vents reduced by 22% and 47% respectively in the re-survey compared to the initial survey. The right y-axis shows the fraction of emissions at each site that are related to tanks. The error bars correspond to 95% confidence intervals around bootstrapped estimates of tank-related emissions.

emissions across the 8 facilities span about two orders of magnitude, indicating that site-level emissions are similarly skewed to that of component-level emissions (see figure 1).

The effectiveness of LDAR surveys in reducing emissions can be studied by tracking leaks and vents from the initial survey during the re-visit. Figure 4 shows the site-level analysis of temporal changes in leaks and vents between the initial survey and the re-survey, along with emissions contribution from tank-related sources. The error bars correspond to 95% confidence intervals, with the uncertainty associated with bootstrapping estimates of tank-related emissions (see methods). It does not include uncertainty associated with the Hi-Flow sampler measurements for other components, as the error (5%) is significantly lower than that derived from tank bootstrapped emissions. Sites that did not have any tank-related emissions do not have any error associated with the bootstrap process. Across the 8 facilities shown here, 93% of the leaks corresponding to 90% of fugitive emissions observed in the initial survey were fixed before the re-survey, indicating a high degree of repair follow-through (i.e. tagged leaks were generally fixed). We find that leaks that were fixed did not re-appear and leaks that were not fixed were still present during the re-survey, demonstrating a high level of leak persistence confirming prior observations [21]. However, overall emissions tagged as leaks only reduced by 22% in the re-survey compared to the initial survey. This suggests that while repair processes can be effective in reducing emissions, frequent LDAR surveys might be necessary for long-term emissions management. Combined with the skewed nature of the leak size distribution (see figure 1), solutions to leak mitigation will require frequent surveys with low-cost and rapid leak detection technologies [36]. In the case of upstream production facilities, this suggests a potential role for cheap fixed sensors, fence-line truck-based monitoring, or aerial surveys using planes and satellites [37].

Leaks only comprise 15% of the overall methane emissions across 36 facilities because tank-related emissions, as the largest single contributor, are classified as vents. By contrast, vented emissions were reduced by 47% during the re-survey, despite near-zero repair after the initial survey—only two emission points classified as vents were fixed by the operator. It is possible that the operator could have improved oversight of tank related emissions based on the findings from the initial survey and reduced the frequency of occurrence of abnormal process conditions such as open thief hatches—this possibility cannot be verified experimentally. Outside of any direct intervention by the operator to reduce emissions, there are other potential causes for the reduction in tank-related emissions. One, tank-related emissions are often intermittent and could have resulted in lower vent emissions during the re-survey purely by chance. Two, emissions from water, chemical, or other storage tanks depend on liquid-level and other process and operation characteristics that might have been different between the survey periods. Three, seasonal equipment like catadyne heaters which vent methane only operate in the winter when needed to prevent chemical lines from freezing. These are further discussed below.

Figure 4 also shows the contribution of tank-related emissions to total emissions at the 8 facilities where post-repair re-survey was completed. The error bars on the fraction of tank-related emissions correspond to 95% confidence intervals calculated at the site-level. Tank-related emissions contributed 64% of the total emissions and 75% of vented emissions (1215 kg CH_4/d, 95% C.I. [1017, 1423]) in the initial survey. In the post-repair re-survey, tank-related emissions contributed to 64% of total emissions and 80% of vented emissions (692 kg CH_4/d, 95% C.I. [561, 869]). Vented emission reduced from a total of 1621 kg CH_4/d (95% C.I. [1423, 1829]) during the initial survey to 863 kg CH_4/d (95% C.I. [732, 1040]) in the post-repair re-survey, a reduction of 47%. Analyzing the underlying component-level emissions points to important insights for future mitigation. Of the 17 tank-related emissions in the initial survey, 12 were specifically from tank-level indicators. During the re-survey, 12 tank-related emissions were found, only one of which was from a tank-level indicator. On average, this reduction in the number of emissions from tank-level indicators between the two surveys reduced vented emissions by approximately 934 kg CH_4/d. Emissions from tank-level indicators are dependent on several factors such as liquid level in the tanks, and ambient temperature, and is independent of any LDAR program. After tank-level indicators, the biggest source of tank-related emissions is thief hatches, accounting for 8% and 28% in the initial survey and post-repair re-survey, respectively. This has two important implications for methane emissions reductions—one, periodic snap-shot measurements may show significant variation in emissions when emissions are dominated by tanks, and two, routine emissions measurements may mask the effectiveness of the repair process in reducing leaks if stochastic tank-related vents are not explicitly considered in analysis. More work is necessary to understand the time evolution of tank-related emissions at oil and gas facilities.

Tanks are one of the largest sources of methane emissions and a targeted and frequent LDAR survey specific to tanks would be critical to effective emissions reductions, even at the expense of LDAR on other equipment. In this context, the state of Colorado provides an example of targeted regulation to reduce tank-related methane emissions [38]. High emissions from tank level indicators and thief hatches point to a need for improving routine maintenance procedures outside of regulatory programs.

In this paper, we presented the first quantitative study of the effectiveness of leak detection and repair programs in methane emissions mitigation at oil and gas facilities, which relies on detailed site visits to quantify emissions before and after LDAR-associated repairs occur. We re-emphasize that this study is limited to facilities of a single operator, and the results presented here cannot be extrapolated to other regions or other operators.

Our analysis of methane emissions provides further evidence to bolster prior observations elsewhere —that emissions distributions are skewed with the top 5% of emitters contributing to about 51% of total emissions, and that tank-related emissions comprise a large fraction of total emissions. Furthermore, our revisit of selected sites following repair provides critical data that can influence future methane mitigation policies. We find that leaks are persistent and LDAR programs are effective—reducing leaks by 90% between surveys. However, despite high repair efficacy, leak related emissions only reduced by 22% between the two surveys, indicating the need for rapid, low-cost, and frequent LDAR surveys. More importantly, regulators and operators should focus their efforts on reducing vent-related emissions. In this context, further clarity on the classification of emissions as leaks and vents will aid the repair process and effectiveness of LDAR programs. In this study, vented emissions reduced by 47% between the two surveys, the majority of which can be attributed to lower tank-related emissions in the post-repair re-survey. Finally, we find that tank-related emissions contribute almost two-thirds of total emissions and points to the need for targeted inspection of tanks.

Given the limited sample size in our study, we call for a more expanded investigation of the effectiveness of LDAR programs in reducing methane emissions. In addition, details of the leak repair process such as average time to fix leaks, fraction of leaking components requiring replacements or work stops, time to repair, and associated costs are still relatively unknown and require further analysis. Future studies that track pre- and post-LDAR emissions would be critical to help regulators develop targeted policies that would be cost-effective and efficient in addressing methane emissions.

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Author contributions

APR, DRS, and ARB designed the research question and developed appropriate methodologies and field protocols. APR and DRS oversaw the field campaign, participated in leak detection surveys, and performed all associated data analysis. RL, JB, AB, YN, SZ, and XB provided periodic feedback on data collection and analysis throughout the course of the study. All authors assisted with writing and editing the manuscript.

Data availability statement

Any data that support the findings of this study are included within the article (as supplementary information) and publicly available at the Harvard dataverse repository [23].

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LETTER

Designing better methane mitigation policies: the challenge of distributed small sources in the natural gas sector

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Abstract

Methane—a short-lived and potent greenhouse gas—presents a unique challenge: it is emitted from a large number of highly distributed and diffuse sources. In this regard, the United States' Environmental Protection Agency (EPA) has recommended periodic leak detection and repair surveys at oil and gas facilities using optical gas imaging technology. This regulation requires an operator to fix all detected leaks within a set time period. Whether such 'find-all-fix-all' policies are effective depends on significant uncertainties in the character of emissions. In this work, we systematically analyze the effect of facility-related and mitigation-related uncertainties on regulation effectiveness. Drawing from multiple publicly-available datasets, we find that: (1) highly-skewed leak-size distributions strongly influence emissions reduction potential; (2) variations in emissions estimates across facilities leads to large variability in mitigation effectiveness; (3) emissions reductions from optical gas imaging-based leak detection programs can range from 15% to over 70%; and (4) while implementation costs are uniformly lower than EPA estimates, benefits from saved gas are highly variable. Combining empirical evidence with model results, we propose four policy options for effective methane mitigation: performance-oriented targets for accelerated emission reductions, flexible policy mechanisms to account for regional variation, technology-agnostic regulations to encourage adoption of the most cost-effective measures, and coordination with other greenhouse gas mitigation policies to reduce unintended spillover effects.

1. Introduction

Global natural gas use is very likely to increase in coming decades [1]. Replacing coal with natural gas significantly reduces almost all air quality impacts, solving a profound challenge facing the rapidly growing megacities of Asia [2]. And in developed economies, natural gas could become more, not less, important because gas turbines readily support flexible power grids with large fractions of renewable power. These trends are strengthened by recent breakthroughs in unconventional gas production that promise decades of gas supply at affordable prices. However, increased use of natural gas has heightened climate concerns because leaked natural gas, which is comprised mainly of methane, is a potent greenhouse gas (GHG) [3, 4].

Globally, methane accounts for 16% of all GHGs in the atmosphere, second only to carbon dioxide [5]. A third of all methane emissions in the United States (US) come from the hydrocarbon (HC) sector (natural gas and petroleum systems) [6]. Recognizing this, the US aims to reduce HC sector methane emissions in 2025 to 40%–45% below 2012 levels [7]. More recently, Canada, US and Mexico agreed to jointly reduce methane emissions [8]. Concurrently, several important developments have brought public attention to the methane leakage issue. Recent incidents—like the Aliso Canyon blowout in California, [9] and deadly explosions in distribution systems in Taiwan [10] and Argentina [11] have increased public scrutiny of gas infrastructure.

However, reducing methane emissions from our HC system is a challenge. There are approximately 1 M oil and gas wells in the US, thousands of processing and handling facilities, and millions of km of transmission and distribution piping below our factories and cities [4]. Each well can contain hundreds of possible points of leakage, and facilities can contain thousands of components. Thus, mitigating methane from the HC sector requires a completely different approach than regulations based on monitoring a small number of large point sources (e.g. power plant CO_2 emissions).

In this context, the US EPA recently finalized updates to the 2012 New Source Performance Standards, henceforth called the *final rule*, to regulate methane emissions from the HC sector [12]. The *final rule* expects to mitigate about 0.46 million metric tons (Mt) of methane in 2025, and result in climate benefits worth 690 M$, at a cost of 530 M$. By comparison, total methane emissions from the oil and gas industry stood at 9.8 Mt (−16%/34%) in 2014 [6]. The *final rule* targets emissions across the natural gas supply chain, including production, processing, gathering and boosting, and transmission and storage sectors. It specifies equipment replacement and operational modifications, as well as periodic leak detection and repair (LDAR) surveys. EPA recommends the use of optical gas imaging (OGI) technology in LDAR surveys, as an alternative to the older standard 'Method-21' (M21), which relied on point-source concentration measurements. OGI technology relies on images and videos of methane leaks that are made visible using infrared imaging cameras. In the *final rule*, OGI-based LDAR is estimated to mitigate 60% or 80% of emissions for semiannual or quarterly surveys, respectively [12]. However, a recent analysis of OGI technologies showed that OGI performance varies significantly with environmental conditions, operator practices, and characteristics of the facility [13]. Therefore, further study is needed to understand whether OGI-based LDAR will result in expected emissions reductions.

Technology effectiveness aside, recent studies of methane emissions provide more cause for concern. For example, many studies have found 'super-emitting' leaks, which are few in number but can cause most of the emissions from a facility. There is also significant regional variation [4] in emissions. To illustrate, a recent study [14] found gathering and processing leakage rates varied from less than 0.2% to about 1% in different regions. Similarly, the Bakken region of North Dakota was found to be leaking up to 6% of produced gas [15, 16] while similar measurements made in Texas [17] show much lower emissions rates. In the face of this diversity, an important question arises: Will the new policies help achieve methane mitigation targets, and if not, are there effective alternative frameworks?

In this work, we analyze the effectiveness of the *final rule* and develop a framework to design improved policies for methane emissions reduction. Our findings are as follows:

1. variation in the baseline emissions estimate between facilities leads to large variability in mitigation effectiveness
2. highly heterogeneous leak-sizes found in various empirical surveys strongly affect emissions reduction potential;
3. emissions reductions from OGI-based LDAR programs depend on a variety of facility-related and mitigation-related factors and can range from 15% to over 70%;
4. while implementation costs are 27% lower than EPA estimates, mitigation benefits can vary from one-third to three times EPA estimates;
5. a number of policy options will help reduce uncertainty, while providing significant flexibility to allow mitigation informed by local conditions.

To support these conclusions below, we first describe our simulation framework. Then we explore uncertainty arising from various facility-related, and mitigation-related factors. We discuss the implications of this uncertainty on the costs and benefits of regulation. Lastly, we develop recommendations that form a framework to effectively mitigate emissions from distributed sources.

2. Methods

General approach: We use an open-source model, the Fugitive Emissions Abatement Simulation Toolkit or FEAST [18], that simulates methane leakage from natural gas facilities at the component level with high time resolution. FEAST uses information about model-plant parameters, generates leaks from an empirical leak-population and applies OGI-based leak detection technology to evaluate mitigation effectiveness. Once 'detected' by the technology module, the leaks are removed from the field. New leaks are added over time in a stochastic manner. All simulations are conducted for a total time of 8 years, with capital costs distributed evenly at 7% interest, as per EPA calculations. At the end of every simulation, the per-site time-averaged leak rate is calculated and compared to the time-averaged no-LDAR leak rate to estimate the additional emission reductions due to policy intervention (see supplementary note 2.1 at stacks.iop.org/ERL/12/044023/mmedia).

OGI technology model: The OGI technology module in this work is modeled after FLIR's GasFind IR-320 camera used for methane leak detection. Images of plumes, as seen by the camera, are simulated using first-principles modeling of the infrared molecular absorption spectrum of methane and

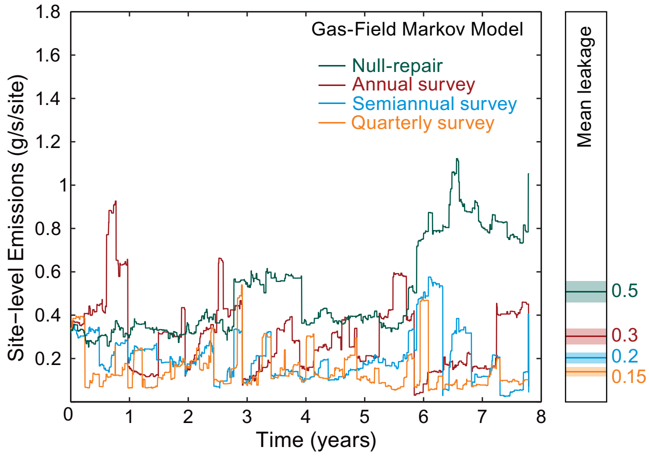

Figure 1. Time-series of a single simulation of OGI-based LDAR programs at gas well-site facility. Four different scenarios are shown: the null-repair scenario (green) shows a facility where leaks are repaired periodically via voluntary mitigation efforts, such that the mean leakage corresponds to publicly-available measured data; and OGI-based LDAR implementation at annual (red), semiannual (blue), and quarterly (orange) survey schedule. The shaded area around mean leakage values (right side bar) represents standard error. Following EPA regulations, all detected leaks are immediately removed from the gas-field.

quantifying the influence of background thermal radiation [13]. Modeling of methane leaks is undertaken using a Gaussian plume dispersion model. We have previously shown that the effectiveness of using an IR camera for leak detection is strongly dependent on environmental conditions, operator practices, underlying leak-size distribution, and gas composition. We use this OGI technology module to evaluate emissions mitigation based on periodic LDAR surveys at natural gas well sites. To realistically model field conditions, we assume that the methane leaks are in thermal equilibrium with the surroundings at a temperature of 300 K, and the composite background emissivity is 0.5. More information on camera properties and other module parameters can be found in online supplementary note 2.2.

Data: Parameters for model plants of all facility-types are derived from the technical support documentation provided as part of EPA's *final rule* [19]. Some analysis also make use of EPA baseline emissions calculations for appropriate comparisons to our model. The population of ≈6000 leaks and the leak-size distribution are taken from various publicly available empirical datasets of natural gas systems in the production [20–22], gathering and boosting [23], and transmission and storage sectors [24]. Economic and policy parameters like capital costs, survey costs, repair and resurvey costs, and gas prices have been modeled after EPA's methodology [19] (also see supplementary note 3).

3. Simulation with an open-source model

FEAST simulates the evolution of leaks at gas facilities, using data from a variety of publicly available data-sets (see online supplementary note 3) to estimate methane emissions and model the effectiveness of LDAR programs. It uses components counts, site characteristics, economic data, and LDAR designs from EPA's analysis [19] (see online supplementary note 4). FEAST also contains an OGI-technology simulation module which simulates the physics of infrared methane imaging cameras [13] (see online supplementary note 2). In FEAST, leaks evolve via a two-state Markov process: each component is in a 'leaking' or 'non-leaking' state with a finite probability of changing state at any given time. The probability that a leak will be found and fixed depends on the LDAR technology employed as well as properties unique to the gas field. Each simulation is run for a period of 8 years with one day time steps.

FEAST contains a 'null-repair' scenario where the total leak rate reaches steady state in the absence of any LDAR program or policy intervention. This is due to a null repair rate that finds and fixes leaks from the system. The null repair rate represents periodic repairs from operators undertaken through voluntary leak mitigation programs. FEAST can then compare this null-repair scenario results to various LDAR implementations. FEAST outputs results showing the time-series of leakage from a particular realization (see figure 1). In the 'null-repair' scenario with no-LDAR performed, the leakage averages 0.5 g s^{-1}/site, with variation due to the random leak generation process. Figure 1 shows the leakage from the same modeled facility under three different LDAR programs: annual, semiannual, and quarterly OGI surveys. We see that the mean leakage in these cases reduces (0.3 to 0.15 g s^{-1}/site) as survey frequency increases.

4. Testing the mitigation policy

Uncertainties in mitigation effectiveness of the *final rule* can be studied systematically under two broad classes: facility-related uncertainty and mitigation-related uncertainty. Facility-related uncertainties refer to effects

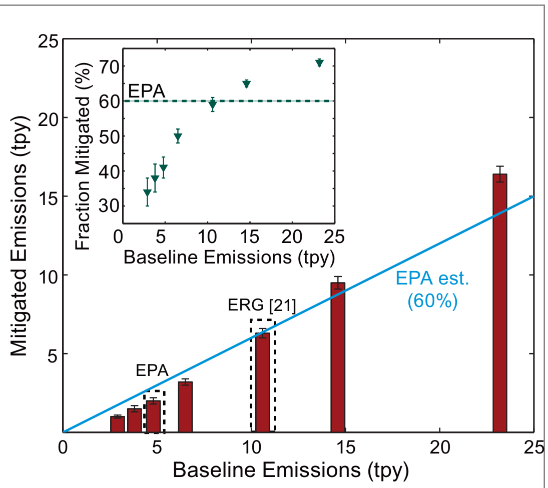

Figure 2. Effect of baseline emissions on the performance of OGI-based leak detection. Effect of baseline emission calculations on the total amount of methane mitigated at a gas well-site production facility. The blue line represents the 60% mitigation level as expected in the *final rule*. (inset) Fractional mitigation as a function of baseline emissions, with the EPA assumption of 60% shown as a dashed green line.

not related to the mitigation program: regional variation in leakage, facility-dependent emissions distributions, estimates of baseline emissions, or chemical composition of the gas resource. Mitigation-related uncertainties are driven by variation in detection technologies and their application in LDAR programs. These uncertainties include minimum detection limits of OGI-based cameras, the influence of environmental conditions during the survey, and sensitivity of OGI to non-methane emissions. We first examine facility-related uncertainties.

4.1. Baseline emissions: effects of voluntary mitigation

An important driver of mitigation effectiveness is the rate of baseline emissions. Baseline emissions are the steady-state leaks in a facility prior to the implementation of policy-mandated LDAR programs. They vary significantly across similar facilities because of regional differences, operator practices, and processing requirements. EPA calculates baseline emissions by multiplying emissions factors for each component at a given facility with the typical number of components at a 'model plant' [19]. Five different model plants with corresponding baseline emissions are specified in the *final rule*: gas well-sites (GW), oil well-sites (OW), gathering and boosting (G & B) stations, transmission (T), and storage (S). The assumed steady-state baseline emissions in a facility will strongly affect the benefits from an LDAR mandate. A higher baseline emissions rate would be associated with higher emission-reduction potential and larger potential cost recovery from saved gas.

To quantify the effect of variation in baseline emissions, we simulate a semiannual OGI-based LDAR survey at a GW site. The leak population and their size-distributions are derived from a survey of ≈400 GW sites in Texas [20] (see online supplementary note 3). Different baseline emissions are modeled by varying the repair rate of the null repair process—a high null-repair rate represents significant voluntary emissions reductions and diligent repair, leading to lower baseline emissions (online supplementary note 5.1). Figure 2 shows the average emissions mitigated in metric tonnes per year (tpy) under different baseline emissions scenarios. The diagonal blue line represents 60% emissions mitigation as expected by the EPA for a semiannual survey. Emissions mitigation range from about 1.1 tpy for a baseline leak rate of 3 tpy to over 16 tpy at a baseline leak rate of ≈ 23 tpy. This corresponds to fractional emission reductions ranging from 37% to 71% (see inset of figure 4). OGI-based reduction fractions vary because of two related processes. While the null repair rate is assumed to repair leaks independent of its size, the OGI-based process removes only the largest leaks. Thus, using OGI-based leak detection technology in a facility with baseline emissions lower than ≈ 10 tpy tends to result in mitigation percentages that are smaller than the expected 60%.

4.2. Effect of skewed leak-size distribution

An even more important facility-related uncertainty is the variability in leak size distribution. Various studies have demonstrated that leak size distributions are highly heterogeneous, with a small fraction of 'super-emitters' contributing a large fraction of total emissions [25]. Because the minimum detection limit of a leak-detection technology is fixed, differing leak-size distributions will significantly affect mitigation even if the total volume of leakage remains constant. Figure 3(*a*) shows normalized cumulative share plots of five artificial leak-size distributions, A–E (see online supplementary note 5.2). The emissions contribution from the largest 10% of emitters varies from 30% in distribution A (least skewed) to 70% in distribution E (most skewed). All facilities exhibit a total emissions volume of ≈10 tpy. We now plot the fractional mitigation resulting from a semiannual OGI survey (figure 3(*b*)). We see that in Facility A, OGI only mitigates 16% of the emissions; while Facility E, with the most-skewed leak population, mitigation exceeds 50%. Clearly, estimates of expected emissions reductions are highly dependent on facility leak size distributions.

We next use six publicly-available component-level leak data-sets from five studies on production [20–22], gathering and boosting [23], transmission [24], and storage [24] facilities (figure 3(*c*)). We simulate OGI based monitoring at the EPA-recommended survey schedule for each facility. In order to directly compare simulation results with EPA-expected emissions reductions, we force each facility to have baseline emission values that corresponds to EPA estimates for that facility type (see online supplementary table S3 for details).

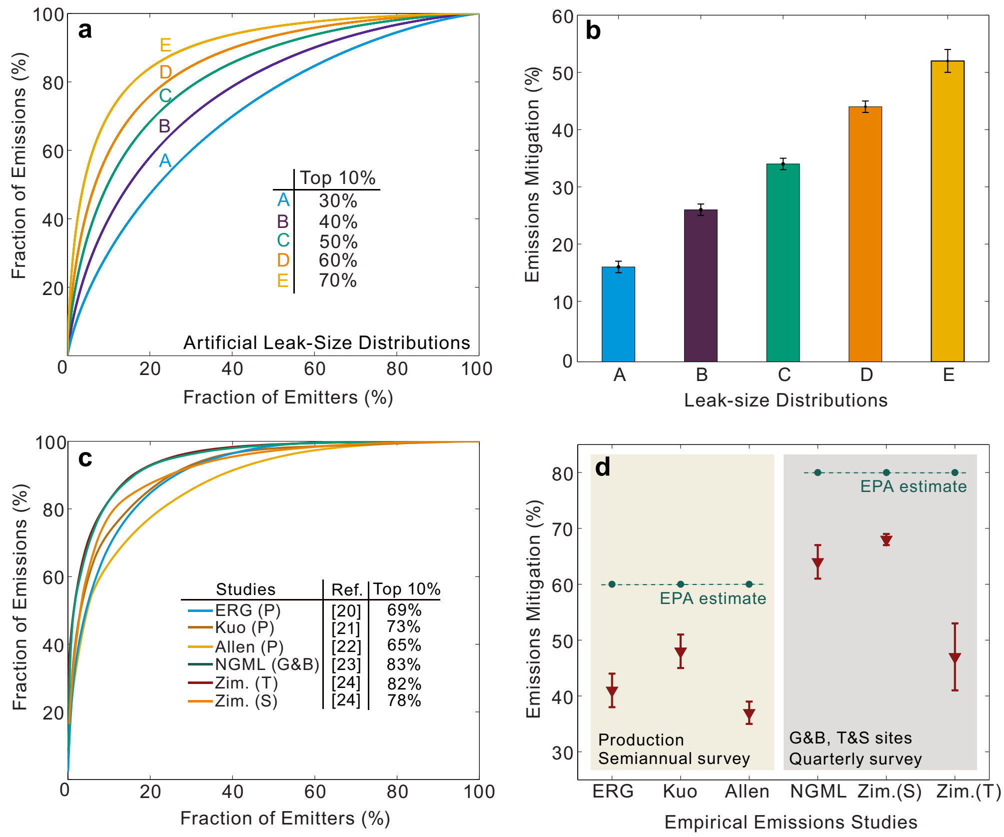

Figure 3. (*a*) Normalized cumulative leak-size distribution for a set of five artificial populations with a baseline emission of about 10 tpy. (*b*) Effect of artificial leak-size distributions shown in (*a*) on fractional emissions mitigation at typical gas well-site production facilities. (*c*) Normalized cumulative leak-size distribution showing the fraction of emitters (*x*-axis) and the fraction of emissions (*y*-axis) for five publicly available empirical studies—three in the production sector (ERG [20], Kuo [21], Allen [22]), and one each in the gathering and boosting (NGML [23]), transmission (Zim.(T) [24]), and storage (Zim.(S) [24]) sectors. (*d*) Emissions mitigation at each of the facilities shown in (*c*) on an OGI-based leak detection survey simulated at the *final rule* recommended frequency. EPA-estimated mitigation values are shown in dashed green lines.

Figure 3(*d*) shows the fractional mitigation for OGI-based leak detection surveys using these datasets with typical OGI survey conditions (see online supplementary note 2.2, but briefly: imaging distance of 5 m and ambient temperature of 300 K). In all cases, we find that simulated emissions mitigation falls short of the EPA-expected 60% (semiannual survey) or 80% (quarterly survey) mitigation levels (green dashed lines).

To explore the production sector cases in more detail: a semiannual LDAR survey only reduces emissions by 37%, 41%, and 48% in the facilities modeled using the Allen [22], ERG [20], and Kuo [21] distributions, respectively. These differences arise despite baseline emissions in all three analyses set equal to EPA-estimated 5 tpy. Variations observed, then, can be attributed to different leak-size distributions in the three studies considered. This shows that assuming a uniform baseline emissions volume for all facilities in a given industry segment is *not sufficient* to drive uniform mitigation benefits. The *final rule* does not model the direct relationship between leak volumes, leak size distributions, and leak detection effectiveness.

4.3. The role of technology and mitigation program

In addition to facility-related uncertainties explored above, mitigation-related uncertainties are also important. Here, we explore the impacts of four mitigation-related uncertainties: imaging distance, detection criteria, ambient temperature, and ambient wind conditions. In all cases, we model GW sites, using a large dataset of leaks generated from peer-reviewed studies (see online supplementary note 5.3 for details).

Figure 4(*a*) shows emissions reductions as a function of imaging distance and survey frequency. Reductions can vary from about 15% (imaging annually at 50 m) to as high as 70% (imaging quarterly at 5 m). Compared to EPA's estimate of 60% reduction from a semiannual survey schedule, we see large variability in mitigation potential. Our results indicate that a 60% emissions reduction from semi-annual surveys is possible only when leaks are imaged at a distance less than 5 m from the leak source. Importantly, the *final rule* does not specify an acceptable survey distance. Furthermore, over 50% of total achievable mitigation at any imaging distance is realized from an annual survey schedule, leading to less variability with changing survey interval than might be imagined. Note that the *final rule* focuses on specifying the time interval of LDAR surveys, but does not specify a more impactful parameter, the survey distance.

Another mitigation-related uncertainty is the detection sensitivity. In OGI-based LDAR, detection

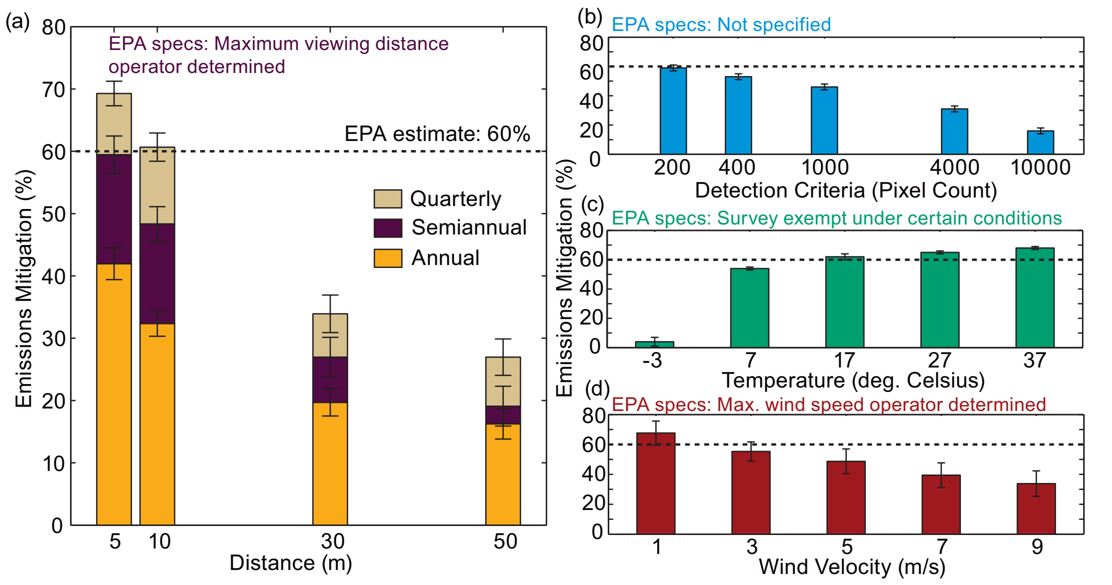

Figure 4. Effect of mitigation-related factors on the performance of OGI-based leak detection. Emissions mitigation at gas well-site production facilities as a function of, (*a*) imaging distance at three different survey schedules: annual (orange bars), semiannual (purple bars), and quarterly (beige bars), (*b*) detection criteria (pixel counts) of the OGI instrument, (*c*) ambient temperature—the temperature of the leak plume is assumed to be 2 K above the ambient temperature, and (*d*) wind velocity. Each sub-figure also notes EPA specifications as mentioned in the *final rule*.

depends on the visual acuity and experience of the operator. We model this factor by varying the minimum number of pixels affected in order for a plume to be detected. Figure 4(*b*), shows that emissions mitigation drops from ≈60% at a detection criterion of 200 pixels to 16% at a detection criterion of 10 000 pixels. In all simulations, a pixel 'registers' the plume if the signal-to-noise ratio (SNR) of the pixel is greater than or equal to 1. Specifying a higher SNR to reduce the occurrence of false positives will also reduce the detection effectiveness [13].

Environmental factors also affect OGI. The effects of temperature and wind velocity are shown in figures 4(*c*) and (*d*), respectively. Mitigation effectiveness abruptly drops near and below 270 K. This abrupt reduction indicates the temperature at which the temperature-emissivity contrast between the plume and its surroundings fall below the SNR of the camera modeled here. Any infrared imaging based detection system should account for significant reduction in detection effectiveness at low temperatures [13]. Wind velocity affects the dispersion of the plume in the atmosphere. Low wind-speeds are preferable to ensure that the plume body remains concentrated and therefore registers a high SNR on camera pixels. This is shown quantitatively in figure 5(*d*) where emissions mitigation reduced from 68% at calm atmospheric conditions with 1 m s^{-1} winds, to about 34% at winds of about 9 m s^{-1}.

5. Fixed costs, variable benefits

The costs of mitigation associated with the *final rule* can be decomposed into three categories: (1) one-time costs to develop compliance plans and other capital expenditures, (2) annual recurring costs associated with conducting LDAR surveys, and (3) costs of the repair and resurvey process. Because of the way the *final rule* is designed, the implementation costs do not vary considerably between similar facilities. On the other hand, the benefits from the expected sale of mitigated gas ('recovery credits'), are highly variable. Here, we analyze these costs and benefits at a GW site on a semiannual OGI-based LDAR schedule. A comparison of economic parameters between our model and that of EPA is summarized in table S6 (see supplementary note 4.5).

Figure 5 shows the implementation costs (red) and recovery credits (blue) at a site as a function of above-explored uncertainties. Two important results include: (1) implementation costs are fairly constant in both our model and EPA estimates, but costs in our model are 27% lower than EPA estimates; and (2) recovery credits vary significantly with mitigation-related and facility-related uncertainties explored above.

For semiannual LDAR monitoring, EPA estimates the implementation cost for all gas well-site production facilities to be \$2285/site (figure 5, red dashed line). By comparison, we estimate a cost of about \$1670 on average, a reduction of 27% from EPA estimates (figure 5, red triangles). The one-time costs and the annual recurring costs of OGI-based LDAR surveys are identical in both models. The difference arises because EPA has higher repair and resurvey costs compared to our model. This occurs because the EPA likely over-estimates the number of leaks found through an OGI-based LDAR survey, as discussed below. It should be noted that both models assume repair and resurvey costs are based on the number of leaks detected rather than the leak size—a reasonable assumption given that studies have shown no

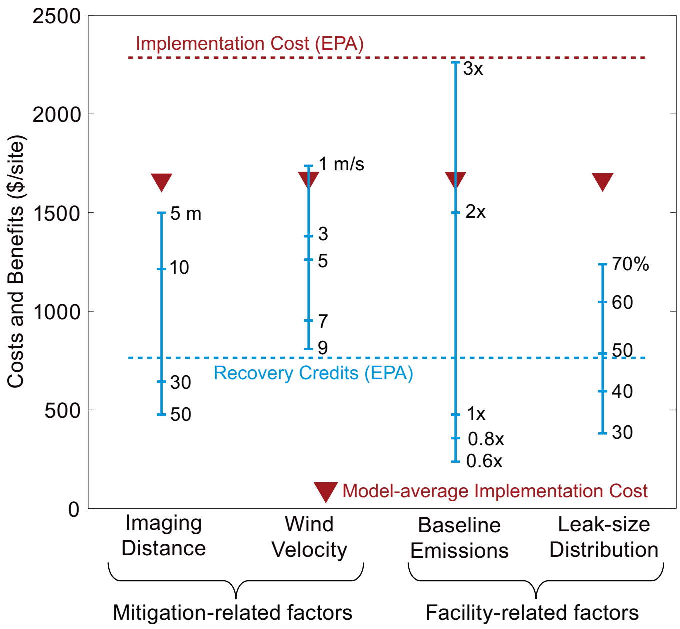

Figure 5. Implementation costs and recovery credits for a semiannual OGI-based LDAR survey at gas well-site facilities. EPA-estimated implementation cost (red-dashed line) is about 27% higher than our model-estimate averages (red triangles). Recovery credits (blue vertical lines) obtained from the sale of captured gas varies significantly based on both mitigation-related and facility-related factors. The tick marks on the recovery credits correspond to various values of the parameters—imaging distance is in m, wind velocity in m s^{-1}, baseline emissions as factors of EPA estimates, and leak-size distribution as the emissions contribution from the largest 10% of emitters. EPA estimate is shown as a dashed blue line.

correlation between repair costs and leak size [23, 26] (also see online supplementary note S5.4).

In estimating repair and resurvey costs, EPA assumes that 1.18% of all components are found leaking using OGI technology [19]. However, this number is inferred from prior measurements of valves in petroleum refineries using an M21 device at the 10 000 ppm screening level [27]. M21 relies on a local concentration measurement (i.e. device returns a ppm CH_4 reading) and concentrations above a screening threshold (i.e. 10 000 ppm) are considered leaking. However, this M21 leak definition cannot be directly applied to natural gas well-sites on an OGI monitoring schedule because of significant differences in detection thresholds. For example, one study which surveyed and quantified thousands of leaks at production sites using both M21 and OGI [20] showed that only 0.175% of components were found leaking using OGI, while 1.07% were found leaking with M21. An earlier EPA study found 2.2% of components leaking with a M21 threshold screening value of 10 000 ppm [23, p. iii], while a recent study using OGI found 0.28% of components leaking [21]. Thus, available evidence suggests that the number of components found to be leaking will be an order of magnitude lower using OGI (0.1%–0.3%) rather than M21 (1%–2%). This difference translates to significantly lower repair and resurvey costs, and hence, lower LDAR implementation costs. In our model the total implementation costs are dominated by the cost of conducting semiannual LDAR surveys: about 80% of GW site costs are from surveys. This results in a case where implementation costs are fairly constant, and independent of mitigation effectiveness.

However, the recovery credits from sale of captured gas vary significantly from EPA's estimates of $764/site. Here, we consider four different factors that affects the amount of emissions mitigated—imaging distance, wind velocity, baseline emissions, and leak size distribution. As imaging distance varies from 5–50 m, the recovery credits decrease from $1499/site to $214/site, respectively. This exemplifies an issue with the *final rule*—by varying an operator-controlled parameter such as imaging distance, the policy benefits vary widely. Similar dynamics are also at play with variations in wind velocity and other parameters. We also consider cases where baseline emissions range from 0.6–3 times the EPA estimate. For facilities with baseline emissions lower than the EPA estimate, the recovery credits available from a semiannual survey are lower than $500/site, covering less than a third of the implementation cost. On the other hand, facilities with high baseline emissions can accrue recovery credits that are higher than the implementation cost, resulting in a highly desirable net-negative cost of emissions control (see online supplementary note 6). Similarly, by varying leak-size distributions, we see that recovery credits vary from $381/site to about $1200/site with more heavy-tailed distribution. This indicates that 'super-emitters' greatly enhance the economics of OGI because the technology favors detection of the largest leaks.

6. Lessons for future mitigation policies

Combining our analysis with other recent findings, we propose improvements to methane mitigation regulation. First, an outcome-oriented policy with targets and an appropriate incentive structure will accelerate emissions mitigation. Second, a mechanism that accounts for regional variability can be more cost-effective. Third, technological flexibility can reduce costs and increase mitigation potential. And fourth, coordination with other emissions mitigation policies like the Clean Power Plan (CPP) [28] will be crucial to prevent unintended emissions spill-over effects. These four recommendations are discussed in further detail below.

Performance oriented targets for accelerated emissions reduction: First, performance based leakage targets based on either a mass-based (absolute emissions cap) or a rate-based (fraction of system throughput) will reduce the variability in mitigation effectiveness. This is because mitigation benefits can vary considerably based on technology, facility characteristics, and individual operator practices. At the same time, LDAR costs are directly proportional to the number of surveys. As we have seen, a poor survey implementation may result in highly sub-optimal emissions reduction. Such a standard perversely penalizes responsible operators with already low baseline emissions by forcing them to implement an LDAR program with minimal benefits. Also, the *final rule* only mandates that the behavior of LDAR is to be performed at some frequency. Such designs raise the possibility of not achieving mitigation goals if operators work to 'check the box' of the regulation requirements at lowest cost. A regulation that instead sets emission targets would allow operators to develop the most cost-effective means to achieve the target. Obviously, such targets would need to be enforced with periodic audits by regulatory agencies.

An outcome-oriented policy objective could have incentive structures that reward emissions mitigation that exceeds targets, while simultaneously penalizing non-compliance. This 'carrot-and-stick' approach can mitigate emissions at a rate faster than what conventional periodic LDAR surveys would allow. To illustrate, 'sticks' can take the form of fines or fees based on actual emission levels and a social cost of methane [29]; 'carrots' can include a system that rewards better-than-required performance (e.g. revenue recycling from fines or preferential permitting for excellent operators). Such target-based approaches would give operators the flexibility to choose mitigation technologies that are uniquely suited for their operations, improving cost-effectiveness.

Flexible policy mechanisms to account for regional variation: National emissions estimates, while important for accounting purposes, should not determine policy for all regions. There is growing evidence from a number of studies that methane emissions vary significantly based on basin characteristics and type of operation. For example, in a study of 114 gathering facilities across eight states, loss rates ranged from a low of about 0.2% to approximately 1% [14]. Measurements at production sites also show very different leak size distribution characteristics—the top 5% of emitters account for about 50% of total emissions in Barnett shale region [20], but over 90% in the Marcellus shale region [30]. Such differences in emission profiles will require different mitigation strategies. In this regard, states like Colorado have provided a template for effective regulation—in addition to LDAR programs at production and compressor facilities, Colorado instituted specific emissions management systems for storage tanks, where 'super-emitters' were more likely to occur. Estimates of expected emissions reductions should be tailored to reflect regional differences, and consequently, should also dictate the stringency and targets for mitigation programs.

Technology-agnostic regulations to improve cost-effectiveness: It would seem logical to specifically target and repair as quickly as possible the small number of super-emitters, resulting in large marginal abatement benefits. In this regard, OGI technology is ideally suited due to its ease in finding large leaks. However, as we saw in figure 4, the performance of this technology is sensitive to environmental conditions and 'detection' relies on the subjective judgment of the operator. Moreover, a semi-annual LDAR schedule could mean that large leaks go un-noticed for up to 6 months. When looking for super-emitters, continuous-monitoring technologies can trade-off sensitivity for lower cost, paving the way for real-time leak detection and mitigation. In addition to numerous technology start-ups, the Department of Energy's MONITOR program [31] is dedicated to developing cost-effective leak detection systems. However, it is unclear if and when such systems will be available on the market. Nevertheless, many other start-up companies promise to conduct leak detection surveys cost-effectively, with the main issue being the difficulty of demonstrating equivalence to EPA approved technologies. Policies should acknowledge future availability of newer and potentially cheaper technologies for leak detection and design regulations that allow for technological flexibility. Indeed, a mass or rate-based mitigation goal, as discussed previously, can be technology-agnostic, resulting in the flexibility that operators and states can use to great advantage, as long as mitigation targets are met and compliance is verified. Such technology-agnostic policies can have the dual advantage of giving operators choice in designing mitigation programs, while ensuring that a pre-determined methane mitigation goal is achieved in a cost-effective manner. As a spillover effect, such policies can establish a robust market for new technologies.

Coordination with other GHG mitigation policies to reduce unintended spillover effects: Finally, we stress the importance of coordinating a methane mitigation policy into the broader context of reducing GHG emissions from different sectors of the economy. The CPP, relies to a large extent on switching high-emitting coal-based power plants with low-emitting natural gas plants. Such fuel-switching, coupled with the shale-gas boom, can significantly increase natural gas production, along with associated methane leakage. Studies have shown that increased methane leakage in the natural gas sector can potentially erode the benefits of the Clean Power Plan [32]. Policy coordination is essential to avoid unintended negative spill-over effects in GHG emissions.

Aside from an emissions perspective, there is also evidence that mitigating all GHGs simultaneously as opposed to focusing on just carbon dioxide will be more cost-effective. Modeling results [33, 34] show that costs are 20%−50% higher when carbon pricing is applied only to carbon dioxide rather than all GHGs, for the same cap on atmospheric CO_2-equivalent concentrations. These results suggest that there might be low-cost options to mitigate non-CO_2 GHGs, in addition to policies that target CO_2 emissions.

While the four policy options discussed here are not cumulative, one can recognize significant co-benefits in implementing these regulations simultaneously. Furthermore, we argue that lessons on effective methane mitigation as described here are widely applicable. Recent work by Kirschke *et al* [35] indicates that emissions from fossil fuels dominate the regional methane budgets in Europe, Middle-East and Russia. Despite global differences in gas composition and extraction systems, methane emissions sources from fossil fuel infrastructure are fairly comparable. Typically, leaks are highly distributed over multiple point sources that include thousands of components like valves, connectors, seals, etc or various points along the millions of km of transmission and distribution pipelines. Each of the components are prone to leaking to varying degrees and at unpredictable times. For this reason, any global effort to reduce fossil-based methane emissions would require mitigation policy that follows the broad recommendations discussed here.

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SVANC VIRTUAL FORUM ON CLEAN ENERGY FOR THE SAN FERNANDO VALLEY

Friday, March 5, 2021
11:00 am – 1:00 pm
Zoom Meeting Online
ID: 987 6658 0221

Climate Change: International Research Institute for Climate and Society, Columbia University. Presented by Dr. Asher Siebert. Power Point Presentation (as PDF)

Sun Valley Area
Neighborhood Council
Mailing Address:
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Hydroclimatic Risks in a Changing World: Examples from Africa and California

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Earth Institute, Columbia University
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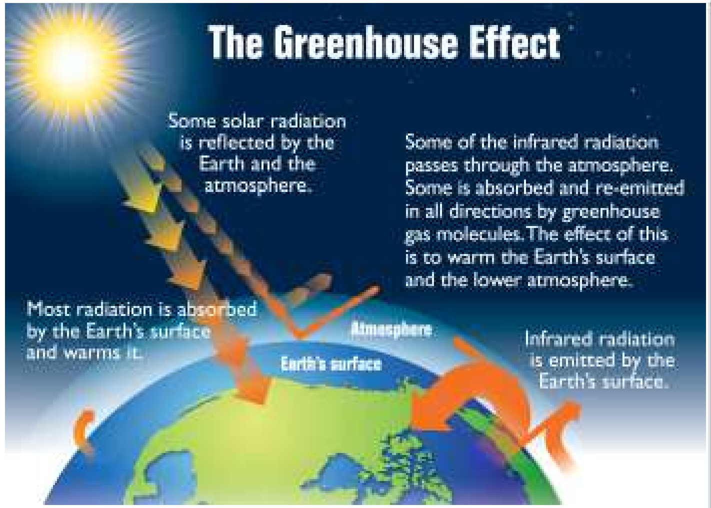
Sun Valley Area Neighborhood Council meeting
March 2021, Los Angeles, California

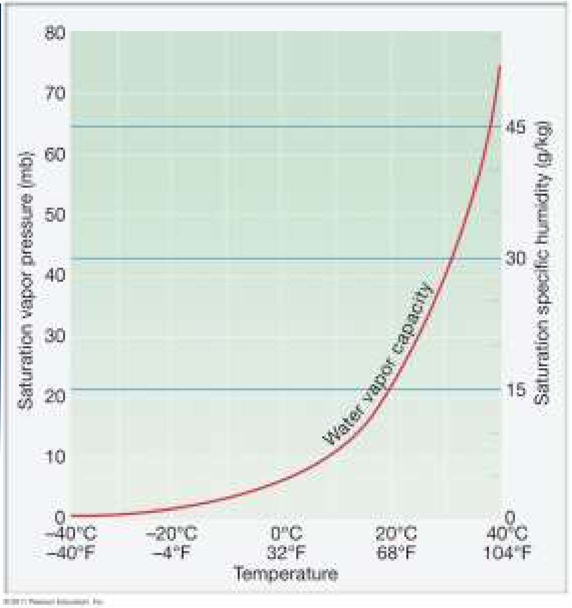
How will climate change effect the hydrologic cycle on global and regional scales?

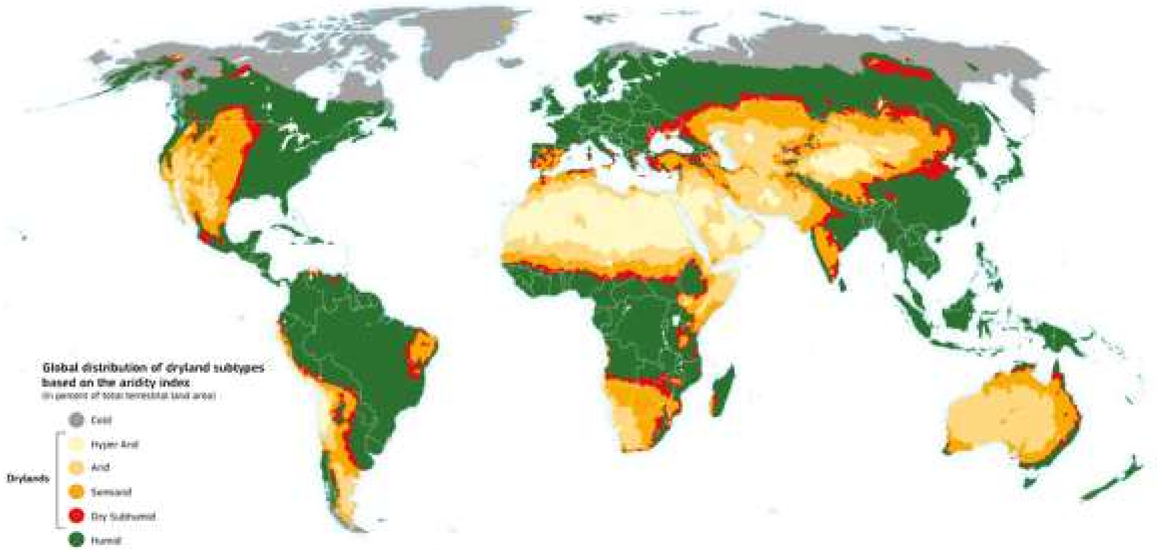
- Climate change is already upon us
- We expect warmer temperatures and many forms of extreme weather
- The hydrologic cycle is likely to intensify
- Intensification of spatial patterns of wet and dry
- Many areas may experience increases of both extremes
- Climate variability and change will pose new challenges of adaptation, but some elements are predictable

Why do we expect these changes?

- Greenhouse effect is growing because of anthropogenic emissions
- Temperature dependence of water vapor capacity
- Expansion/poleward shift of the arid regions of the subtropics
- Weaker jet streams because of reduced equator to pole temperature gradient
- Increased frequency, intensity and size of “blocking events” in a warmer world

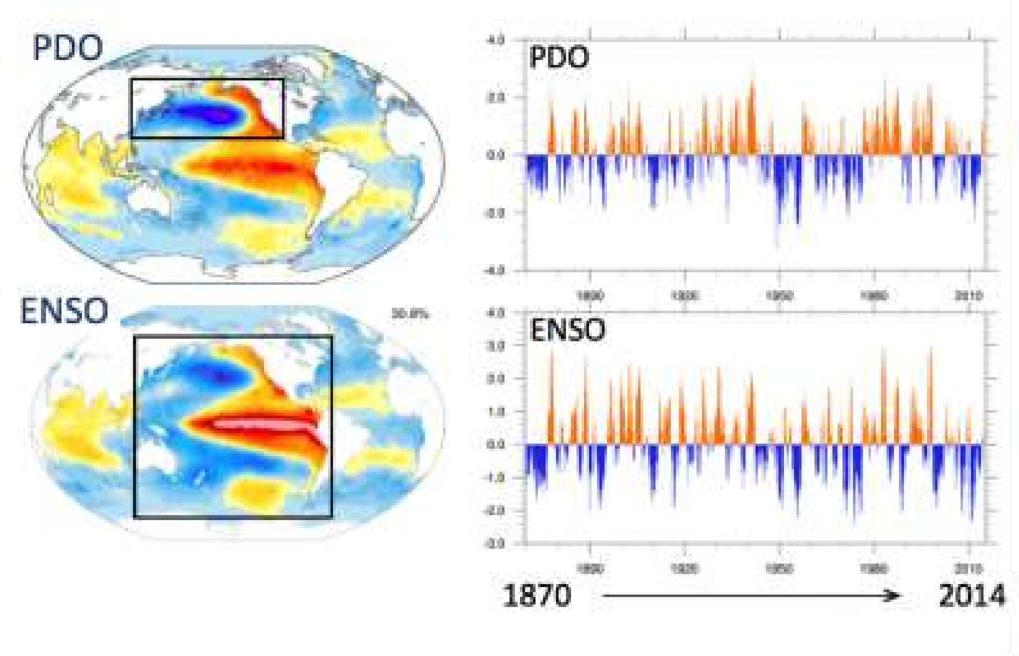


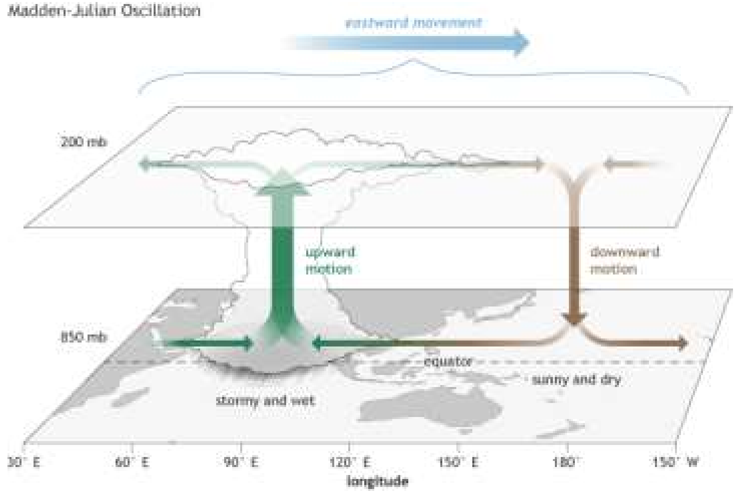


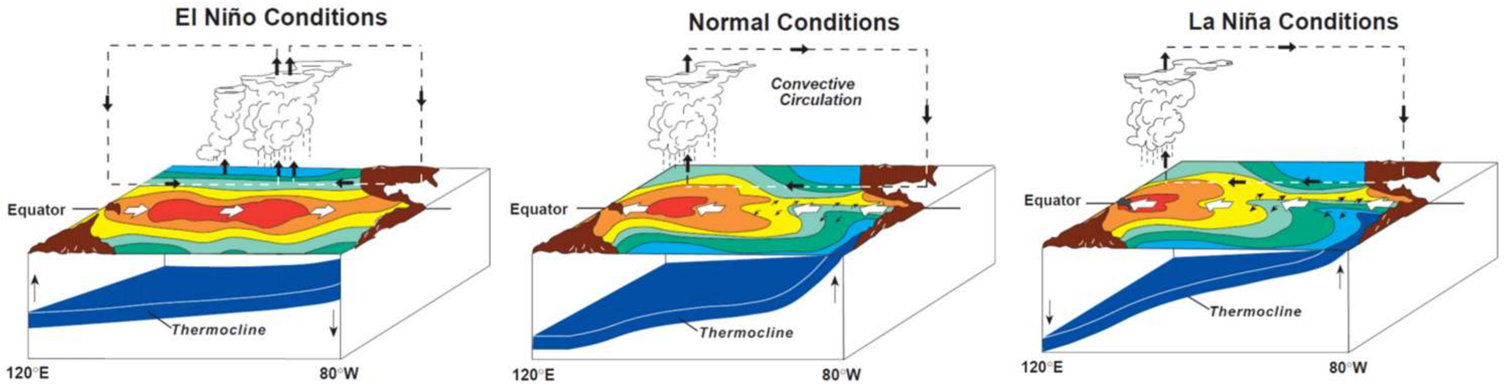


Sources of predictability for hydroclimate

- On decadal/multi-decadal time scale, Atlantic and Pacific Decadal variability (AMO and PDO)
- On interannual time scales, patterns such as El Nino (ENSO) and Indian Ocean Dipole (IOD)
- Annual seasonal cycle
- On sub-seasonal time scales, patterns such as Madden Julian Oscillation (MJO)



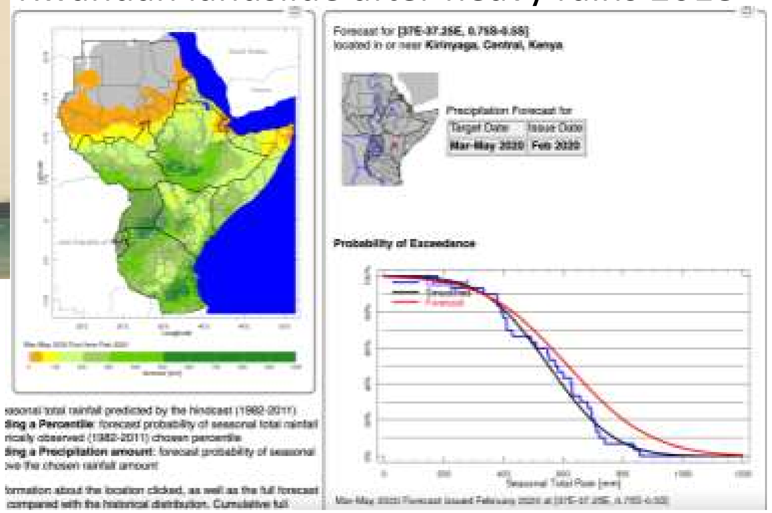




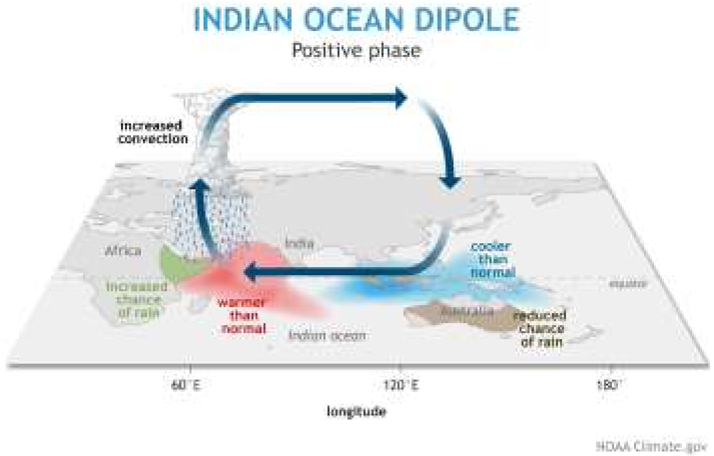
IRI work on predictability and capacity building in Africa

- ACToday and CCAFS Rwanda
- Multi-model calibrated forecasts with flexible forecast format
- Trying to address hydroclimate risks and impacts across sectors
- National trainings and capacity building
- International collaboration through Regional Climate Outlook Forums
- Sources of seasonal predictability for E. Africa: ENSO in OND, IOD
- Sources of seasonal predictability for W. Africa: SST patterns in Atlantic, heating over Sahara

Rwandan landslide after heavy rains 2018



ICPAC maprooms



Recent hydroclimatic extremes around the world

- Drought in Horn of Africa
- wet 2019/2020 season with locust invasion
- Multi-decade drought in California, extreme wildfire seasons
- Australian heat waves and brush fires Jan 2020
- Heat waves and flooding in south Asia
- Various tropical cyclones

Kenya 2020 locust plague

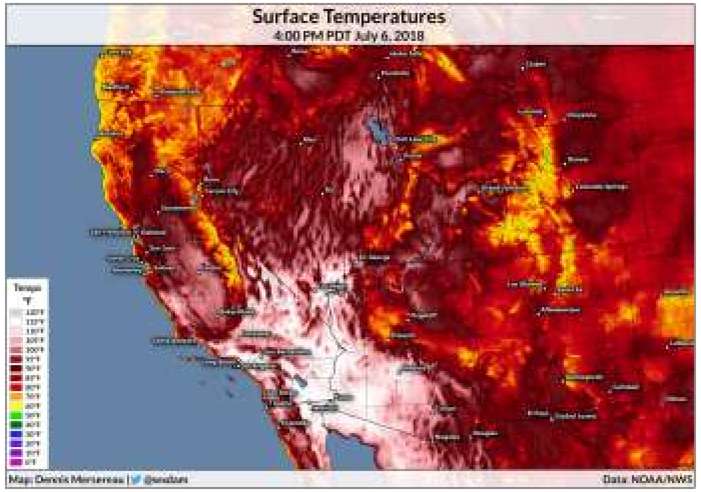
Somalia 2017 severe drought

GG Bridge, CA 2020 extreme wildfires

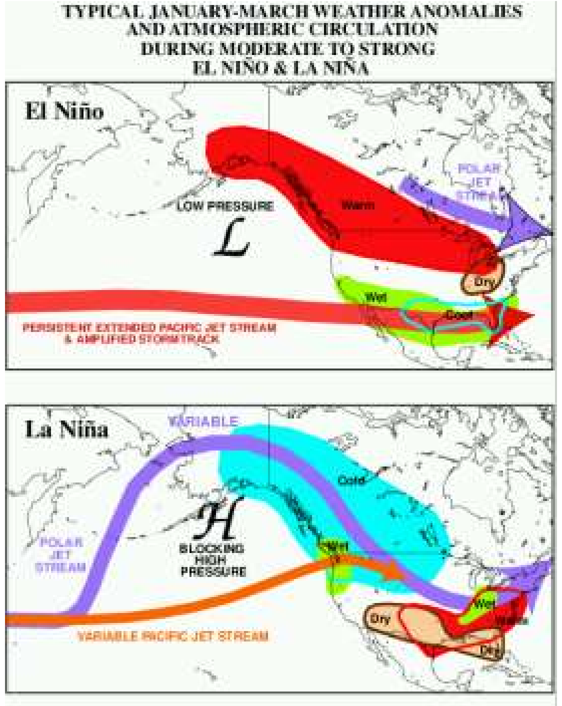
Bahamas 2019 after Hurricane Dorian

Hydroclimatic extremes and predictability in California

- Droughts, heat waves, wildfires, power failures, health impacts
- Atmospheric river events with enormous rainfall, mudslides and snowfall at high elevation
- Tree ring and other paleoclimate analysis – evidence of long-term drought in the SW in the past
- Wildfire damage and deforestation can elevate mudslide risk
- Predictability from ENSO and MJO signature in Indian and Pacific Oceans
- But each event/season is different: [ENSO myths]
- Antecedent conditions – winter rainfall/snowfall deficits and summer drought/heat waves strongly correlated
- My hope with NOAA proposal: build MME system forecasting system for antecedents/ seasonal prediction and S2S predictors for within season heat wave risk



Deadly mudslides following AR heavy rains, Santa Barbara county 2018



How can California prepare?

- Need for more investment in better forest management
- more firefighting capacity
- wiser suburban development plans
  - too much increase in wildfire exposure risk through sprawl into forested hillsides
- different construction materials and building codes for heat and fire stress
  - Challenging – because most non-wood materials more expensive and carbon intensive, but wood products can contribute to deforestation and are more vulnerable to fire
- better early warning systems
- better proactive policies for heat health and power sector
- improved insurance infrastructure and incentives
- better social protection for vulnerable
  - power outages and health effects from heat waves may disproportionately impact the poor
  - CA large homeless population, wealth/vulnerability stratification
- water conservation and/or expanded desalination
- reduce irrigation of state's agriculture

Firefighter battling the 2018 Camp Fire

Intentional controlled burn of forest understory

Large wood framed houses close together on a forested hillside

Land subsidence due to irrigation

What can we do at the global scale?

- Vote green – make sure elected representatives acknowledge the realities and impacts of climate change
- Ambitious international cooperation that builds on Paris 2015
  - even strict adherence to NDCs from Paris will likely only limit warming to 3-3.5 degrees by 2100
- Advance renewables as much as possible (both technical R&D and market penetration)
  - evidence has shown that political and regulatory efforts are far too slow, inconsistent and ineffective to solve the problem top down;
  - as renewables become more cost-competitive per Kwh, market forces could take over and drive the transition
  - Consider whole life cycle of new technologies: eg. fully electric cars emit more than hybrids if your home energy is still fossil fuel based
- Reform fossil fuel industry
  - Remove fossil fuel subsidies and limit or remove investment in fossil fuels
  - Create more regulatory pressure on fossil fuel industry
  - Support working class people transitioning out of fossil fuel industry jobs and those most affected by gas and energy price increases
- Invest in early warning systems, improved prediction systems, and measures to protect vulnerable people and assets
- Diet, lifestyle, etc..