Energy Choice and Life Cycle Analysis
A Framework for Evaluating Options, Impacts, and National Energy Choices

Energy Transition Summit

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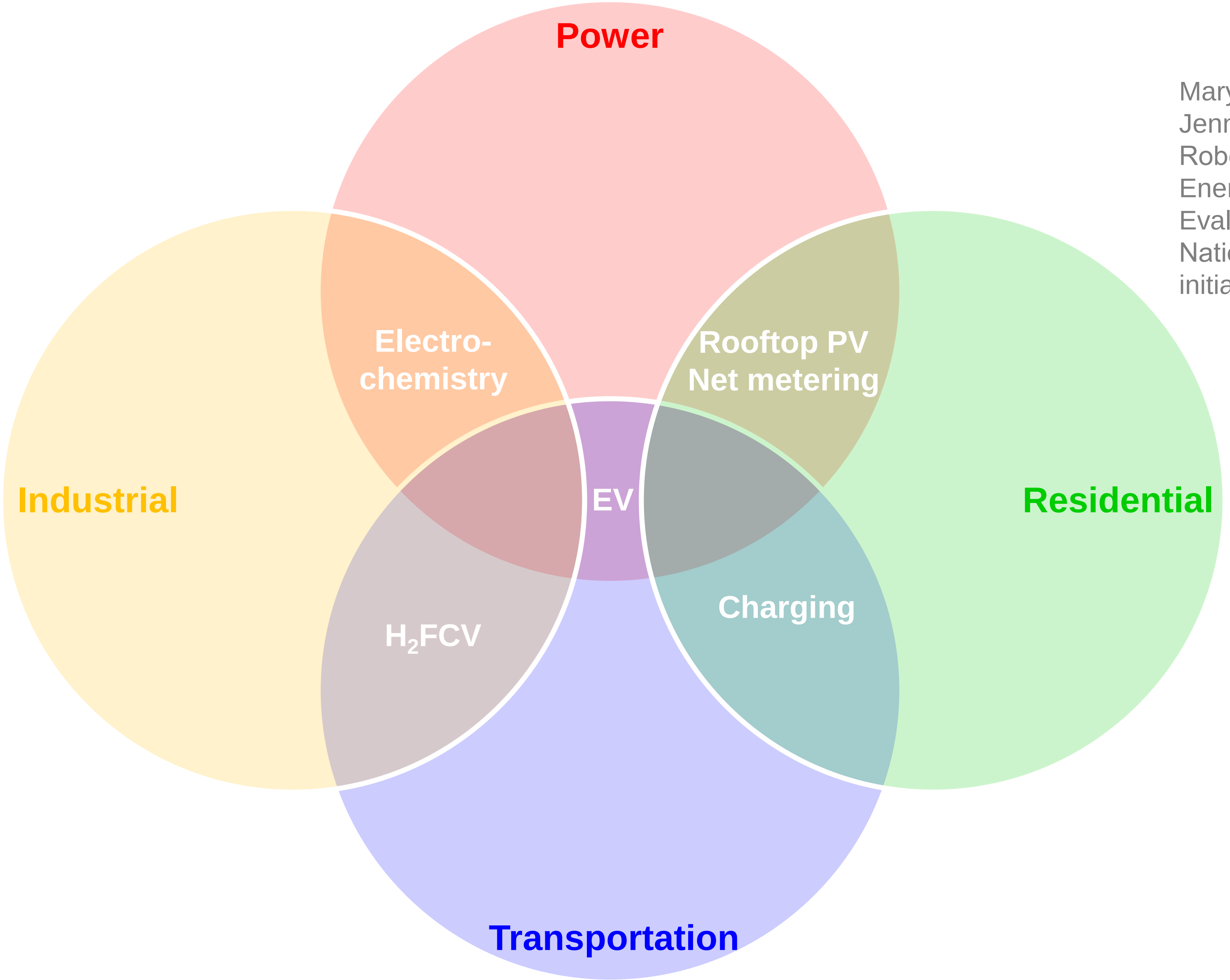
GRAND ENERGY CHALLENGE

Global energy demand is projected to grow significantly;
and
The world needs to dramatically reduce greenhouse gas emissions while developing and deploying clean, affordable, reliable energy solutions.

Today's energy systems are undergoing major transformations, which are leading towards greater convergence and inter-sectoral integration – Understanding the implications of these dynamics requires novel tools that provide deep systems-level insights

Carbon Capture, Utilization, and Storage

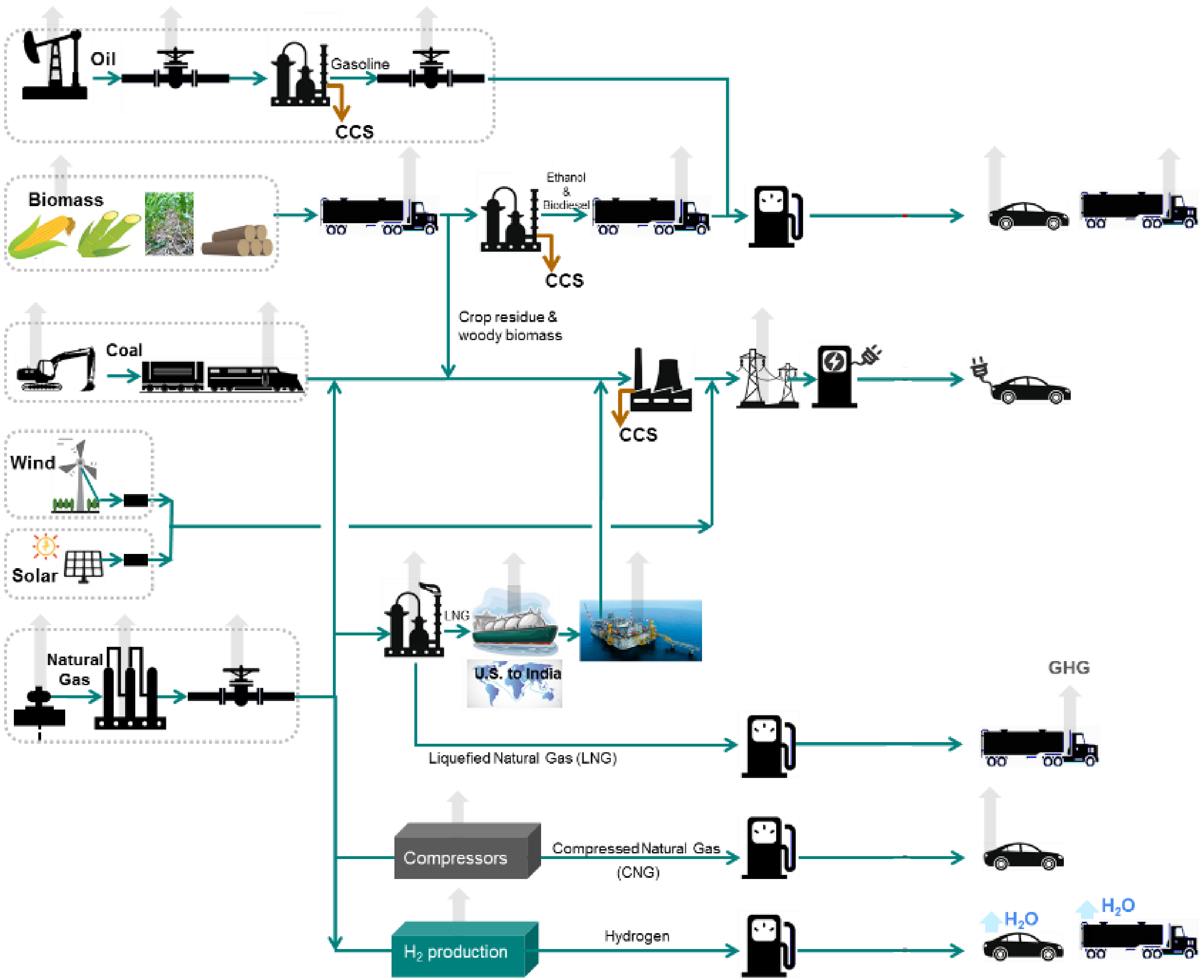


Maryam Arbabzadeh, Emre Gençer, Jennifer F Morris, Sergey Paltsev, Robert C Armstrong, "Plausible Energy Futures: A Framework for Evaluating Options, Impacts, and National Energy Choices" MIT Energy initiative Working Paper.

Storage and Low-carbon fuels

MITei

A central feature of today's changing energy landscape is the growth in alternative technology options and the increasing uncertainty



Sustainable Energy Systems Analysis Modeling Environment (SESAME)

The modular structure of our platform allows the analysis of a very large number of conventional and novel pathways – More than 1000 energy pathways are embedded in this framework, capturing ~90% of energy-related emissions.

A key focus for SESAME is to provide insights into the feasibility, scalability, and emission reduction potential of various technology pathways as the energy system restructures.

UPSTREAM

Renewable

- Biomass
  - Corn
  - Corn stover
  - Cellulosic bolt-on
  - Forest residue
  - Biogas
- Solar
  - Photovoltaics
  - CSP*
- Wind
- Hydro
- Wave & Tidal
- Geothermal

Fossil

- Natural gas
  - Conventional
  - Shale gas
  - Tight gas
  - Coal bed
- Oil
  - Conventional
  - Tight oil
  - Oil sands
  - Oil shale
- Coal
  - Bituminous
  - Sub-bituminous
  - Lignite

Other

- Ore, chemicals, etc.

MIDSTREAM

Gas

- Compression
- Separation
- Liquefaction
- Pipeline / Tank / Ship
- Flare

Liquid

- Separation
- Pipeline / Rail / Ship / Truck

Solid

- Drying
- Crushing / Milling
- Truck / Ship / Rail
- Uranium ore transportation

PROCESS

Heat & Power

- Sub-critical
- Super-critical
- Gas turbine
- Combined cycle
- IGCC **
- Steam generation
- Combustion
- Nuclear

Industrial

- Refinery
  - Gasoline
  - Diesel
- Biorefinery
  - Ethanol (Fermentation)
- Gasification

Production Processes for:

- CNG / LNG
- Dimethyl ether
- Methanol
- Polyethylene
- H_2
  - Steam methane Reforming
  - Partial Oxidation
  - Auto Thermal Reforming
  - Electrolysis
- Iron & Steel
- Cement

CCUS ***

CO_2 separation

- Absorption
- Adsorption
- Oxy-combustion

CO_2 compression

CO_2 Utilization

- Enhanced Oil Recovery
- Solvent
- Chemical production

CO_2 Storage

- Aquifer
- Unmineable beds
- Enhanced Oil Recovery

GATE TO USER

Power

- Transmission lines
- Distribution lines

Heat

- Steam

Gas

- Filling stations
- Pipeline / Tank / Ship

Liquid

- Pipeline / Rail / Ship / Truck

Advanced Storage

- Flow batteries
- Pumped hydro
- Molten salt
- Li-ion

Solid

- Truck / Ship / Rail

END USE

Products

- Electricity
- Heat
- Liquid Products
  - Gasoline
  - Diesel
  - Ethanol
  - Methanol
  - Dimethyl ether
  - Liquefied natural gas
  - LPG
- Gaseous Products
  - Compressed NG
  - Hydrogen
- Solid Products
  - Cement
  - Iron & Steel
  - Polyethylene

End Users

Residential

- Solar thermal
- Advanced lighting
- Cont. commissioning
- Advanced control

Transportation

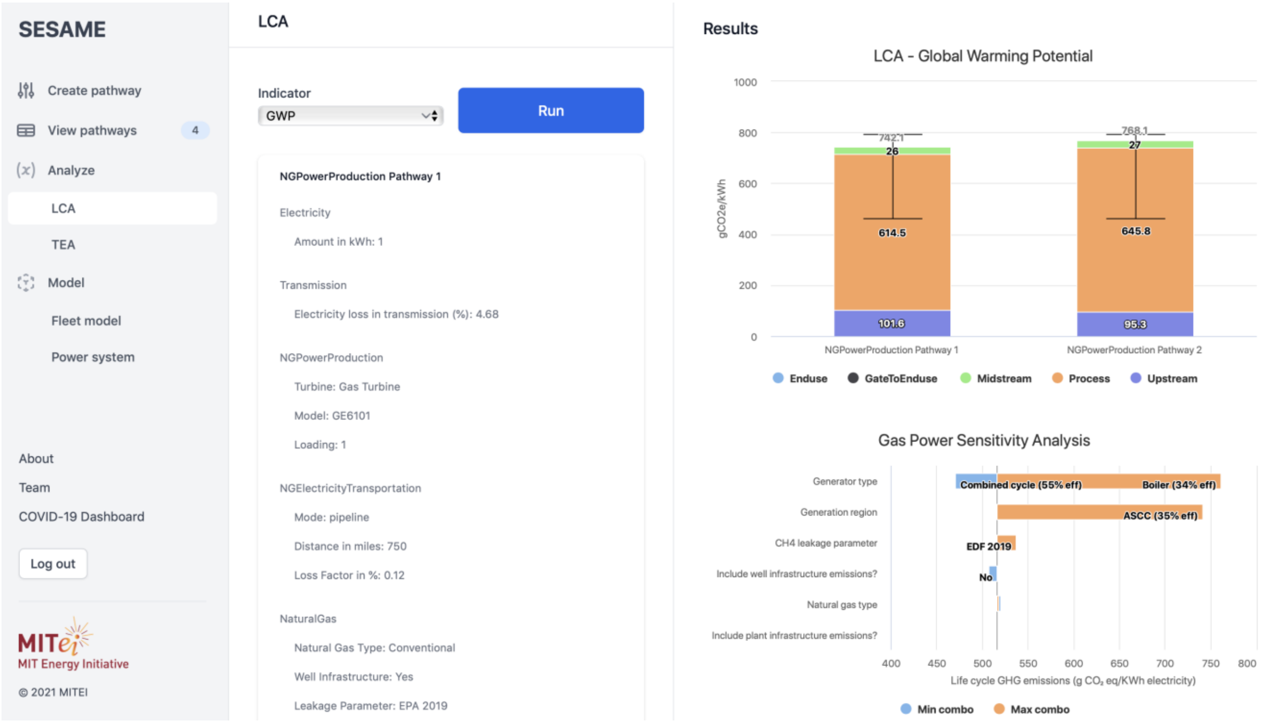
- HDV
- LDV Technologies
  - ICEV
  - Hybrid
  - EV
  - FCV
- Engine efficiency

Industrial

- Efficiency
- Process enhancement & intensification

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

We have developed SESAME to understand the impact of all relevant technological, operational, temporal and geospatial variables on the evolving energy system



Sustainable Energy Systems Analysis Modeling Environment

- – Assess and compare technology options
- – Perform technology and system scenario analysis
- – Explore the implications of market and policy dynamics
- – Perform cross sector comparisons
- – Assess impacts arising from standard vs. best practices

For Economy-Wide Modeling we enhance the MIT Economic Projection and Policy Analysis (EPPA) model and connect EPPA to SESAME

Major goals of EPPA:

Projection of regional and global energy, land use, environment, and economy

GDP
Sectoral output
Sectoral international trade
Energy mix by type
Electricity mix by type
Land use by type (crop, pasture, natural grass, managed forest, natural forest, other)
GHG emissions (CO_2, CH_4, N_2O, HFC, PFC, SF_6)
Air pollutants (CO, VOC, SO_2, NOx, NH_3, black carbon, organic carbon)

Emission projections are integrated with MIT climate model to perform scenario analysis and uncertainty analysis for climate variables (temperature, precipitation, sea level rise, water stress, etc)

Connection to SESAME:

Sustainable Energy Systems Analysis Modeling Environment (SESAME) provides technological and operational details and life-cycle analysis of different pathways

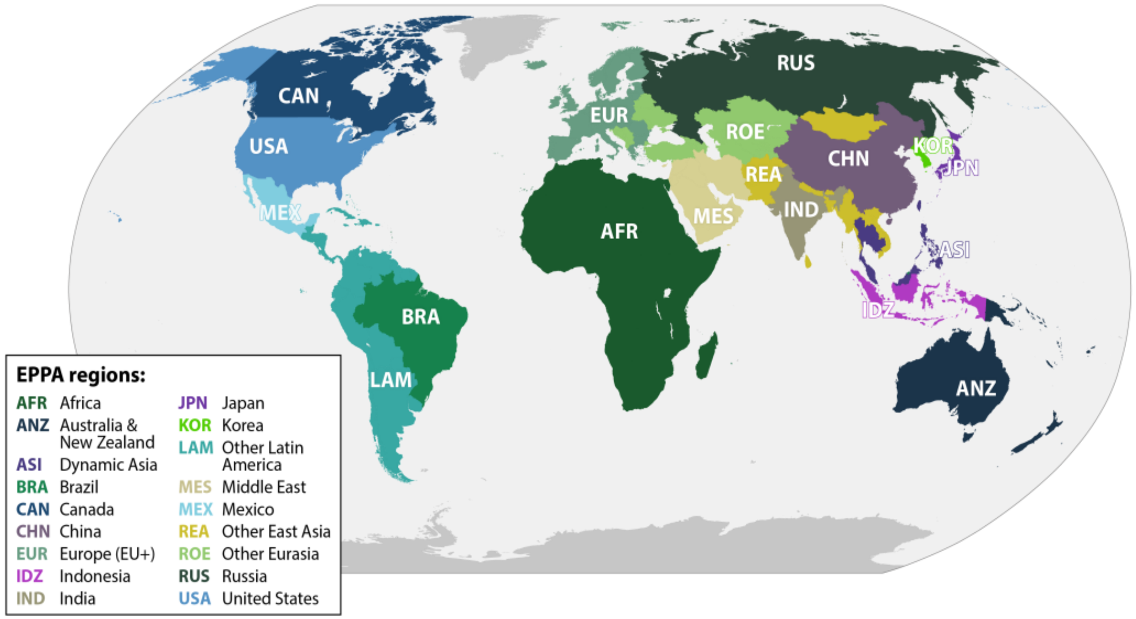
EPPA provides to SESAME economy-wide and global projections for energy mix, electricity mix, and fuel prices

SESAME informs EPPA about the changes in emission coefficients over time associated with particular technologies (e.g., car manufacturing), detailed fleet dynamics, and technology granularity for parameterization of new technologies (e.g, hydrogen, e-fuels, storage)

Linking EPPA and SESAME enhances the benefits of both approaches and provides actionable information to decision makers

Base Setting of the MIT Economic Projection and Policy Analysis (EPPA) Model

Major goals:
Energy, economy, land use, GHG and air pollutants projections



Representation: Global coverage, All sectors of economy

I&S: Iron & Steel
NMM: Non-Metallic Minerals (Cement, etc.)
NFM: Non-Ferrous Metals (Aluminum, etc.)
OEIN: Petrochemicals (Fertilizers, Olefins, etc.)

Non-Energy
- **Crops**
- **Livestock**
- **Forestry**
- **Food**
- **Energy Intensive Ind.**
- **Manufacturing**
- **Services**
- **Industrial Transport**
- **Household Transport**

Vehicle Types
ICE (gasoline & diesel)
Plug-in Electric
Battery Electric
Hydrogen

Biofuels
Current generation (Ethanol from Biodiesel)

Advanced biofuel

Energy
- **Crude oil**
- **Refined oil**
- **Liquid fuel from biomass**
- **Oil Shale**
- **Coal**
- **Natural gas (conv., shale, tight, CBM)**
- **Electricity**
- **Synthetic gas (from coal)**

Technologies
Conv. Fossil (coal, gas, oil)
Adv. Fossil (NGCC, Adv Coal)
Coal with CCS
Coal + Bio Co-firing w/ CCS
Gas with CCS
Gas with Advanced CCS
Nuclear
Advanced Nuclear
Hydro
Solar
Wind
Wind with Backup
Solar with Backup
Biomass
Biomass with CCS

Expansion: Industrial CCS options, Hydrogen production options, Hydrogen Pathways, Direct Air Capture, CO_2 utilization pathways

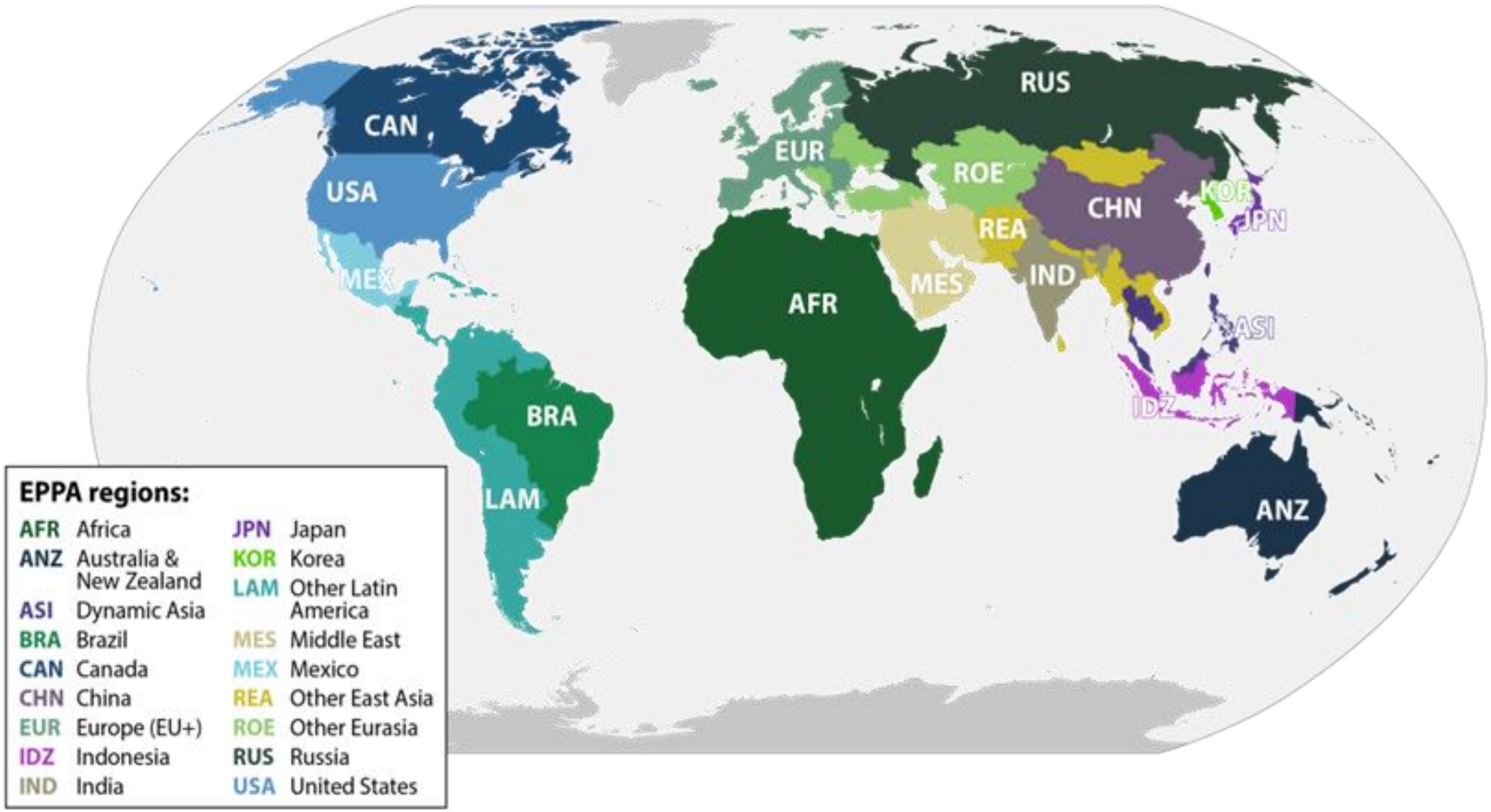
Model Features: Theory-based; Prices are endogenous; International Trade; Inter-industry linkages; Distortions (taxes, subsidies, etc.); GDP and Welfare effects

Trade-off: Aggregated representation of regions, sectors, technologies

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

For IEA-GOT project we separated Norway and Singapore from the base EPPA aggregation

Base Regional Aggregation



New Separate Regions

Norway out of EUR (Europe)

Germany out of EUR (Europe)

Singapore out of ASI (Dynamic Asia)

EPPA Updates for new regions:

Reference Economic Growth
Population (UN)
Energy Balances (IEA)
Greenhouse gas (GHG) emissions (CH_4, N_2O, PFC, HFC, SF_6) and air pollutants (SO_2, CO, NH_3, NOx, VOC, black carbon, organic carbon) (EDGAR)

We also disaggregated additional sectors: Metals Production, Cement, Chemicals, and Transportation by mode (Land, Air, Water)

Base Sectoral Aggregation

Non-Energy
- Crops
- Livestock
- Forestry
- Food
- Energy Intensive Ind.
- Manufacturing
- Services
- Industrial Transport
- Household Transport

Energy
- Crude oil
- Refined oil
- Liquid fuel from biomass
- Oil Shale
- Coal
- Natural gas (conv., shale, tight, CBM)
- Electricity
- Synthetic gas (from coal)

Vehicle Types
ICE (gasoline & diesel)
Plug-in Electric
Battery Electric

Biofuels
Current generation (Ethanol from Biodiesel)

Advanced biofuel

Technologies
Conv. Fossil (coal, gas, oil)
Adv. Fossil (NGCC, Adv Coal)
Coal with CCS
Coal + Bio Co-firing w/ CCS
Gas with CCS
Gas with Advanced CCS
Nuclear
Advanced Nuclear
Hydro
Solar
Wind
Wind with Gas Backup
Wind with Biomass Backup
Biomass
Biomass with CCS

New Separate Sectors

Energy-Intensive Industries
- METL (Metals and Metal Products)
- NMM (Cement)
- CHM (Chemicals)
- EINT (Other Energy-Intensive Industries)

Industrial Transport
- ATP (Air Transport)
- WTP (Water Transport)
- OTP (Other Transport)

To assess the pathways, we used the following scenarios

Scenario	Description
Paris Forever	Current (as of March 2021) Paris Nationally Determined Contribution (NDC) targets are met by all countries by 2030 and retained thereafter
Paris 2°C	Paris Nationally Determined Contribution (NDC) targets are met by all countries by 2030, after which there is an emissions cap based on a global emissions trajectory designed to ensure that the 2100 global surface mean temperature does not exceed 2°C above pre-industrial levels with a 50% probability
Accelerated Actions	More near-term actions are taken relative to Paris 2°C (including those planned changes to NDCs announced in April 2021), and global emissions are consistent with ensuring that the 2100 global surface mean temperature does not exceed 1.5°C above pre-industrial levels with a 50% probability. Note: Climate results are shown for a slightly different 1.5°C scenario (Paris 1.5°C) that uses a global emissions price.

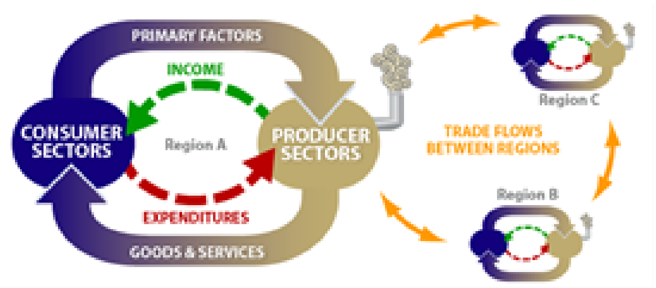
With the main focus on the Accelerated Actions (Accelerated Paris) scenario

IEA-GOT Project: Scenarios and Data Exchange

Scenarios to 2050

Paris Forever
Paris to 2C
Accelerated Actions

Energy Prices, Energy Mix, Electricity Mix for three scenarios

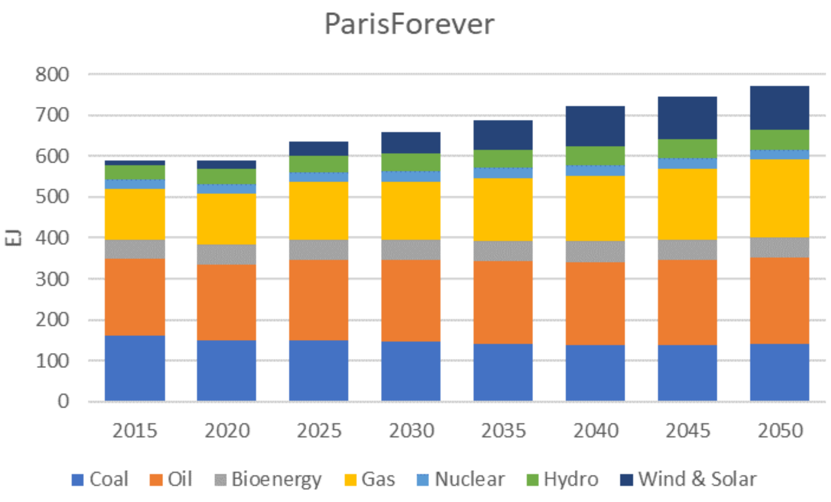


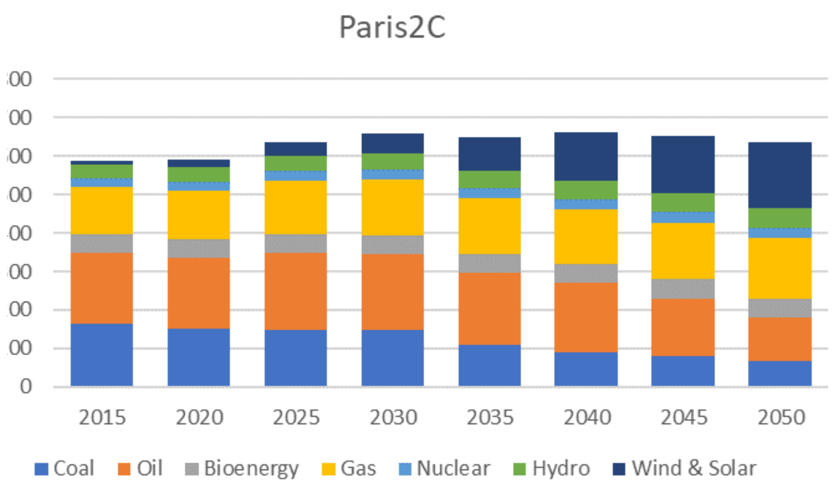
EPPA

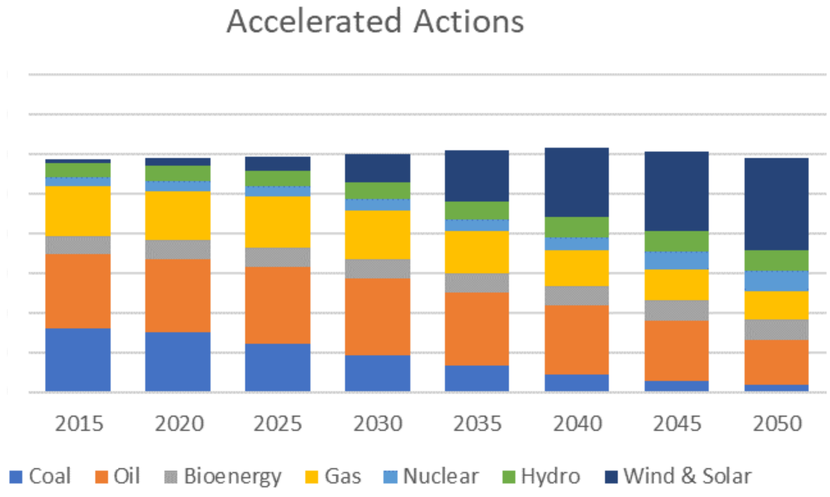
SESAME

Technology Detail, Detailed LCA/TEA, Fleet Dynamics

Global Primary Energy





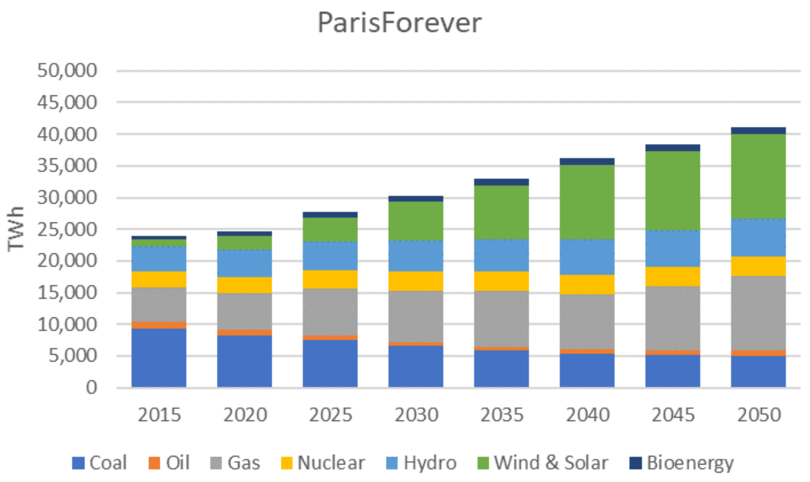


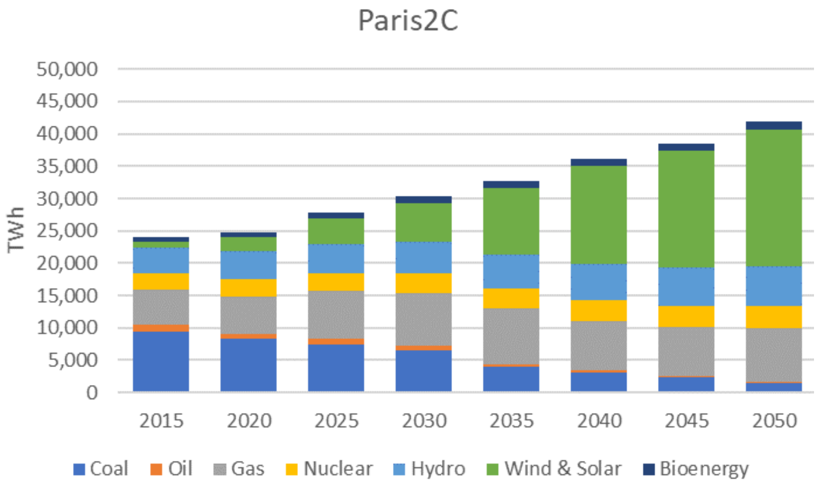
Global primary energy use in the *Paris Forever scenario* grows to about 770 exajoules (EJ) by 2050, up by 31% from about 590 EJ in 2020. The share of fossil fuels drops from the current 80% to **70%** in 2050. Wind and solar – **6**-fold increase.

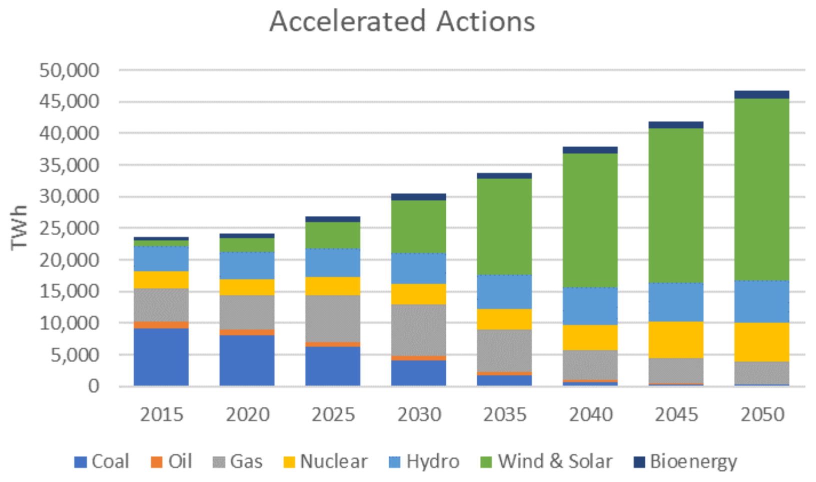
In the *Paris 2°C* scenario, the fossil fuel share drops to about **50%** in 2050, wind and solar energy grow almost **9** times from 2020 to 2050.

In the *Accelerated Actions* scenario, the fossil fuel share drops to about **34%**, wind and solar energy grow almost **13** times from 2020 to 2050.

Global Electricity Production



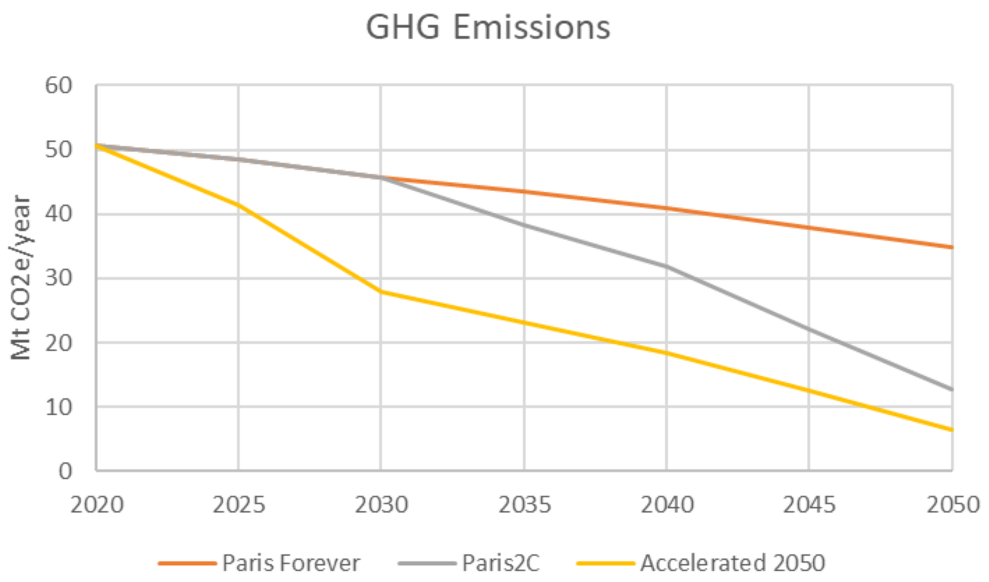




In the *Paris Forever* scenario, global electricity production (and use) grows by 67% from 2020 to 2050. In comparison to primary energy growth of 31% over the same period, electricity grows about twice as fast, resulting in a continuing electrification of the global economy.

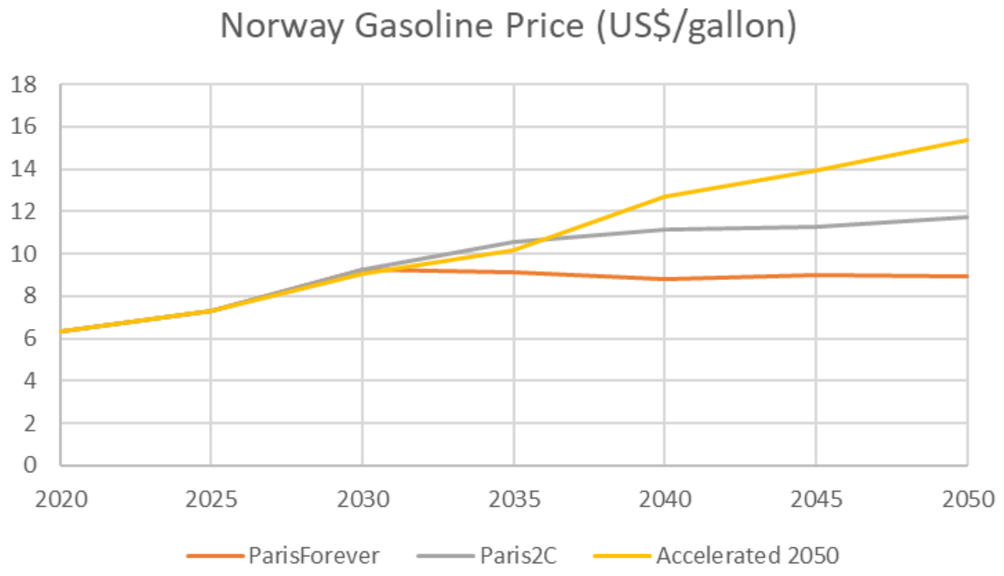
Electricity generation from renewable sources becomes a dominant source of power by 2050 in all scenarios, providing 70-80% of global power generation by midcentury in the climate stabilization scenarios

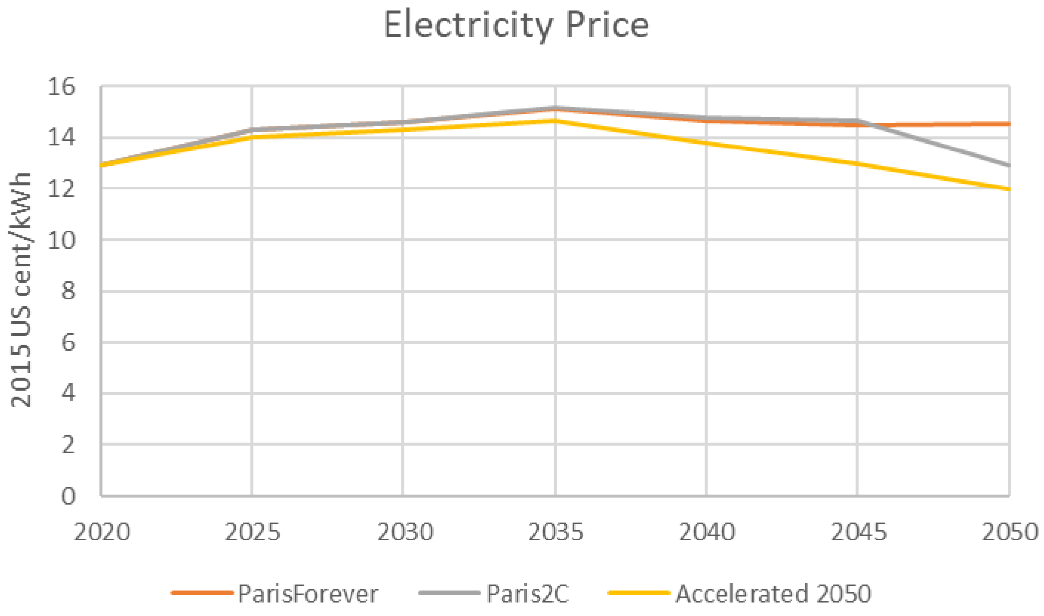
Selected Results for Norway



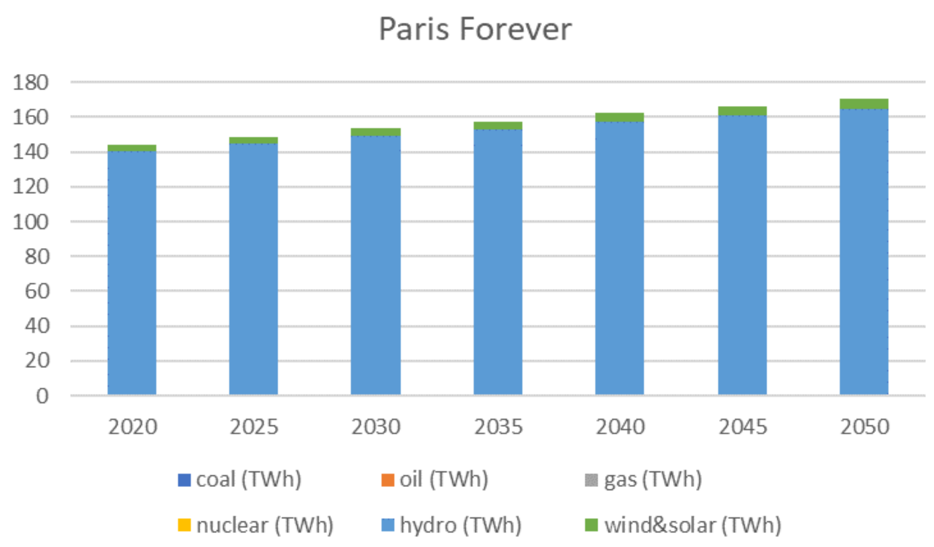
GHG Emissions (not counting emissions from land-use change) are reduced by almost 90% by 2050 relative to 2020

Projected land-use and forestry sink is about 20 Mt CO_2/year

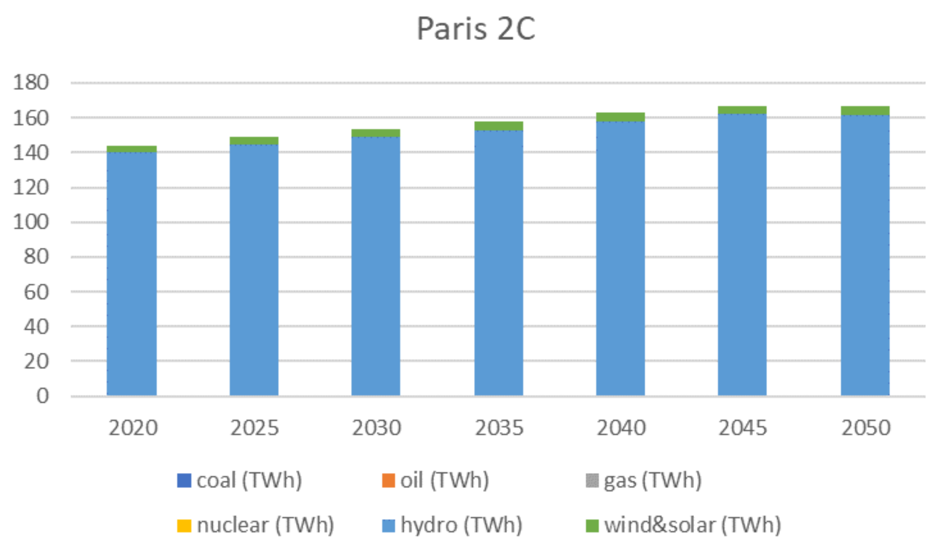


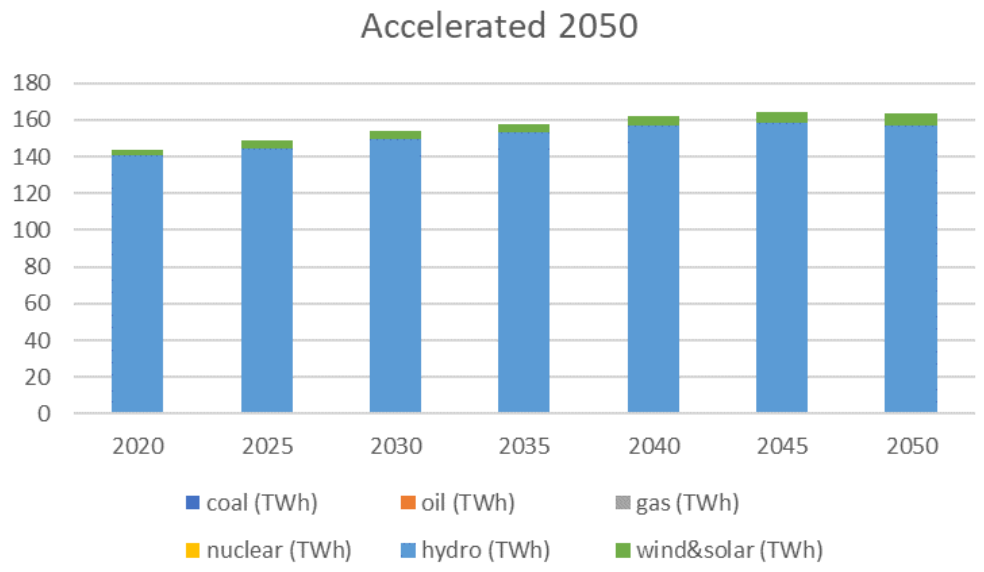


Norway Electricity Mix

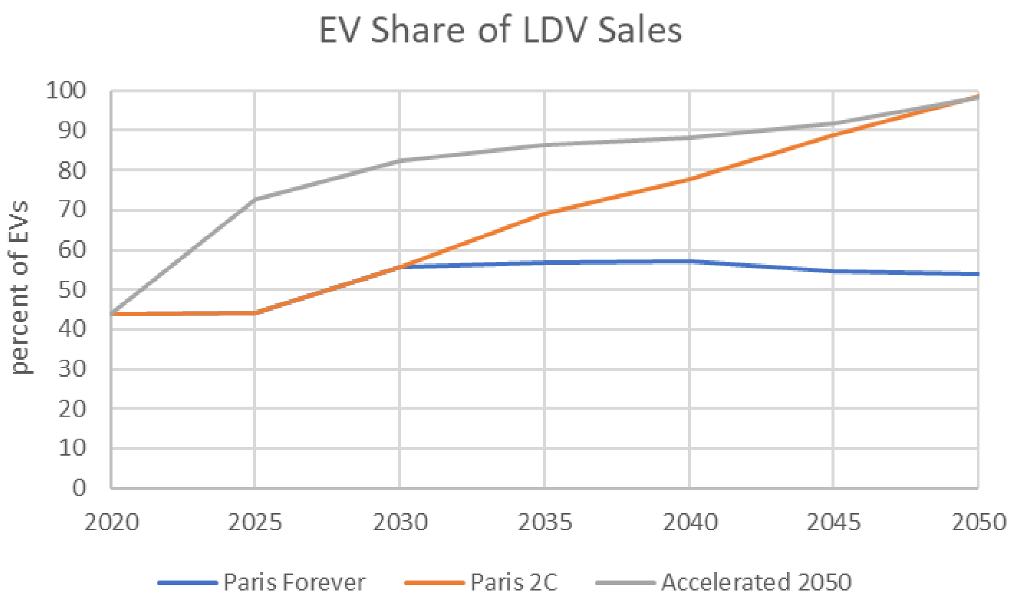


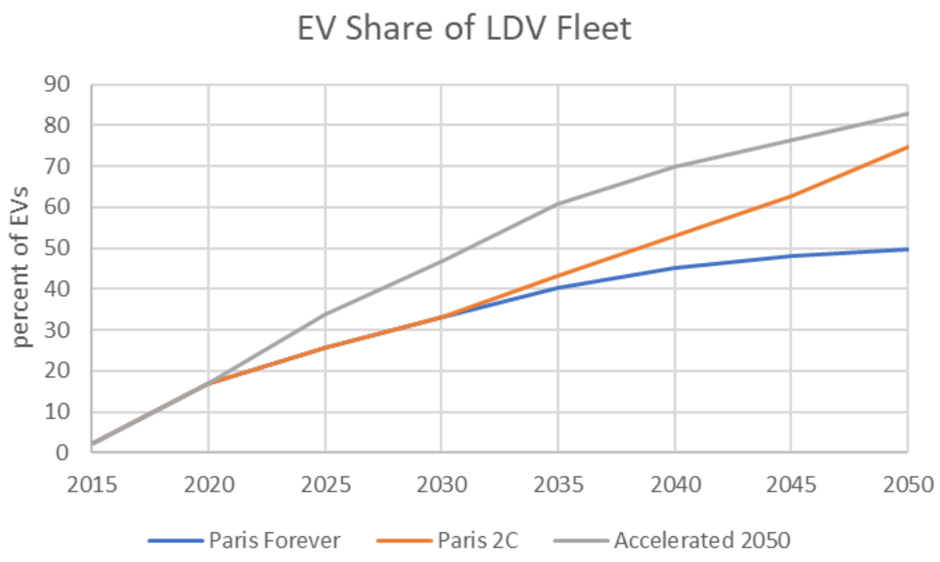
Norway electicity mix stays hydropower-based with some increases in wind generation



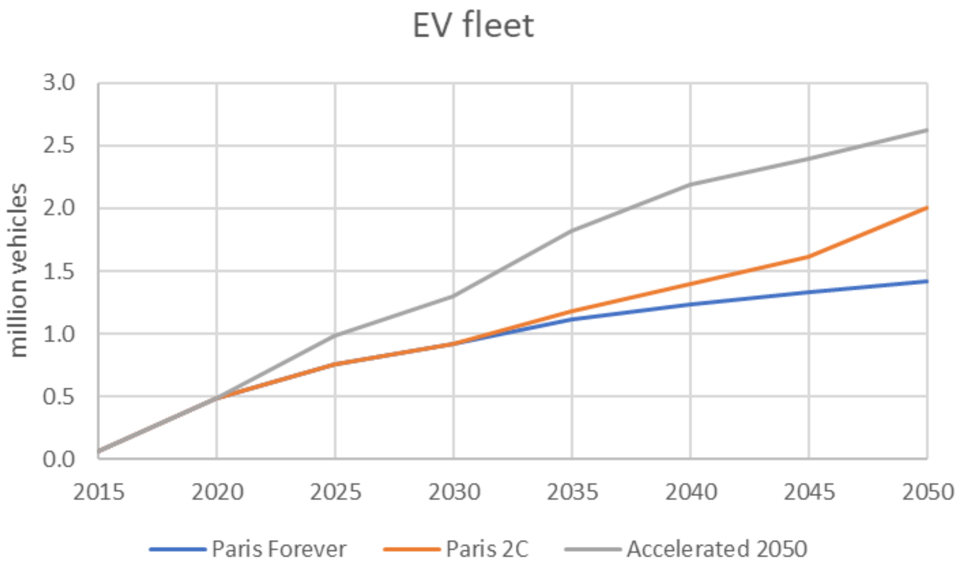


Norway Electric LDVs sales and fleet (stock) projections

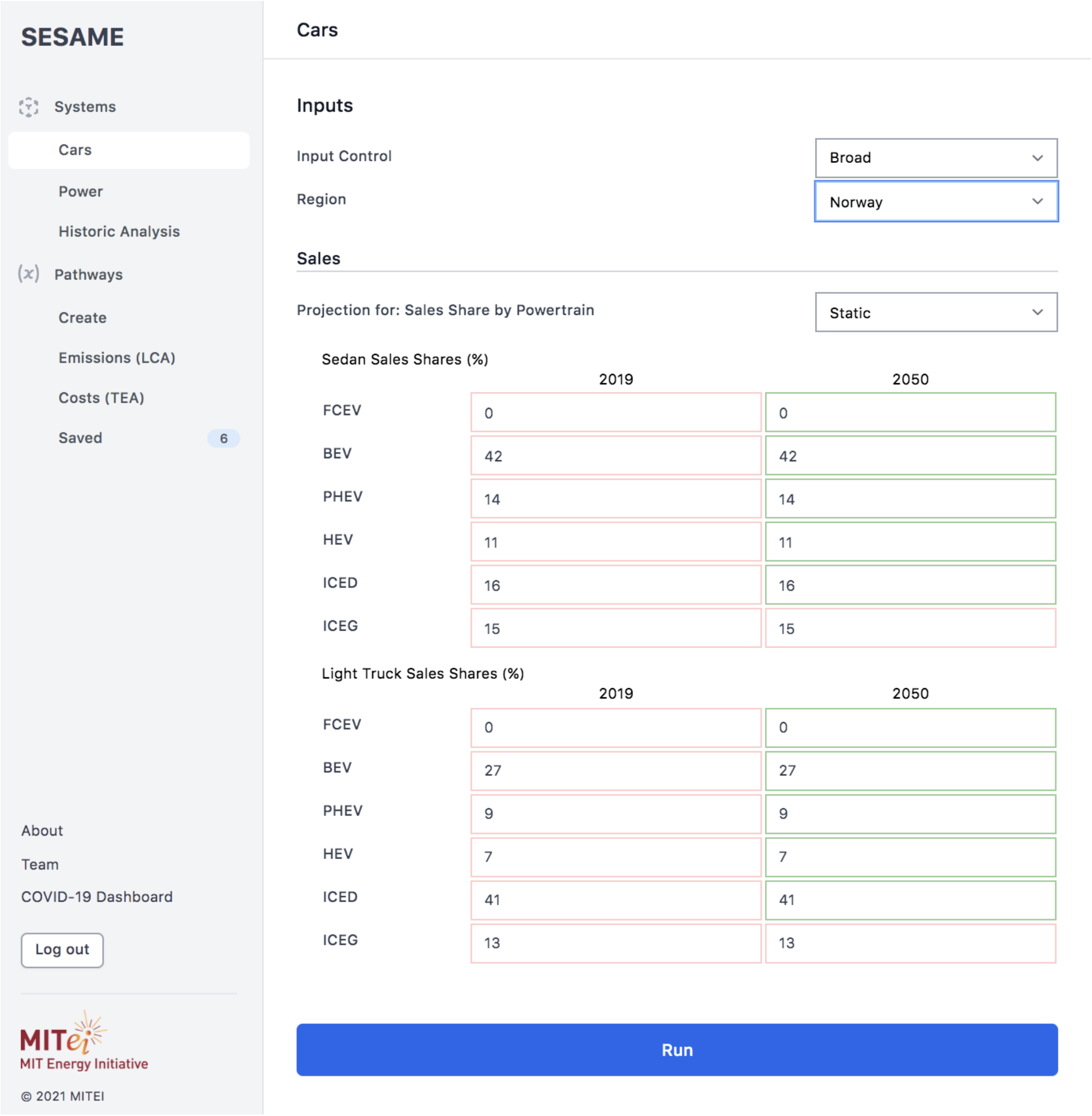




In the Accelerated Actions scenario, EV sales grow fast from about 50% in 2020 to about 85-90% in 2030-2035 and to about 100% by 2050



Norway Fleet Model



- 60% of new registered cars in Norway are electric

EPPA Informs SESAME

- Electricity mix
- Energy mix
- Sectoral supply and demand
- Prices (fuels, electricity, etc.)
- Regional differences
- Trade flows
- Sectoral and regional emission profiles
- …

EPPA projections can be passed to SESAME (an LCA model) to generate more realistic calculations.

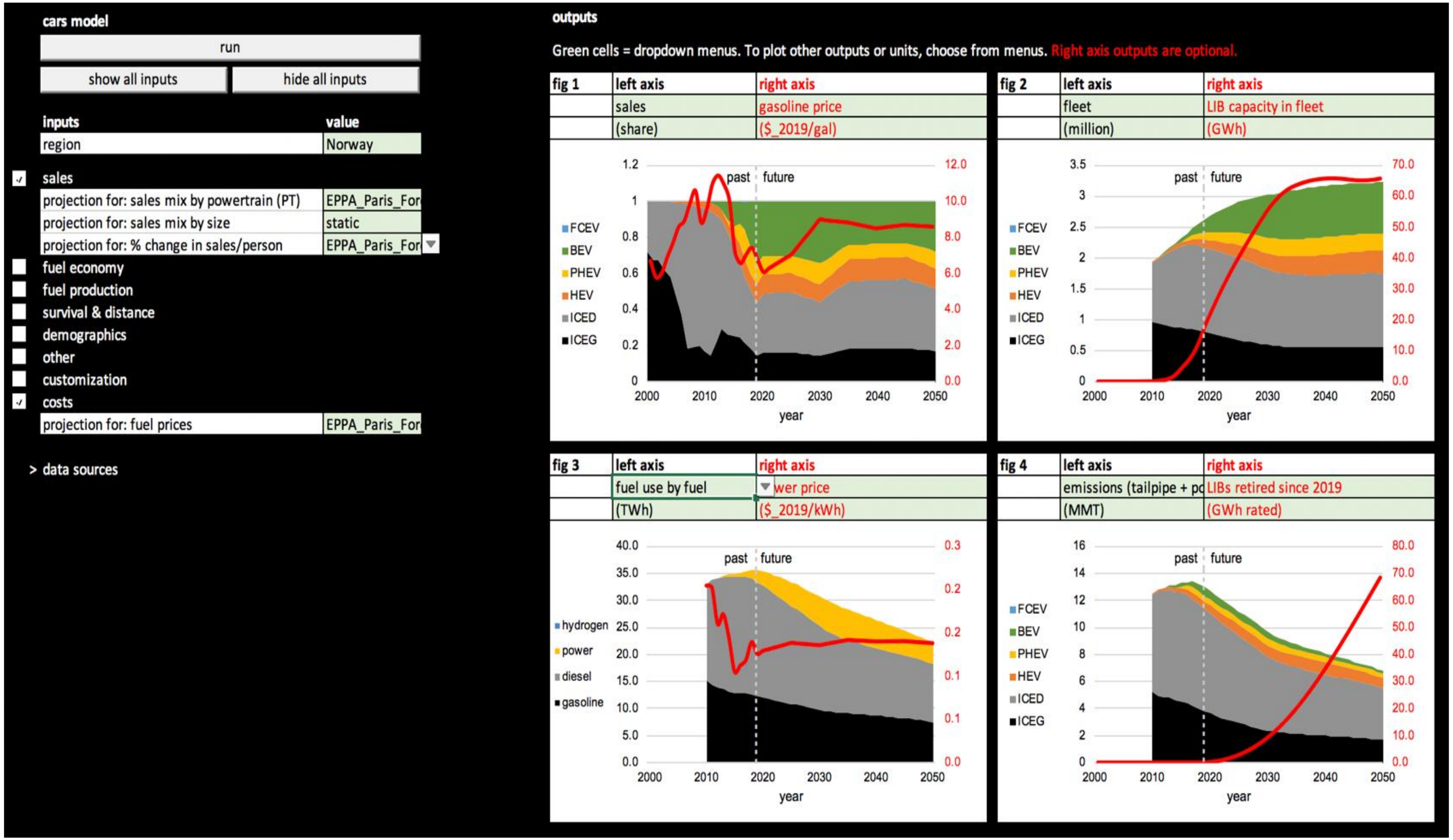
Combining the strengths of SESAME with the strengths of EPPA is an important avenue for creating a robust decision-making framework for the assessment of plausible energy futures.

SESAME fleet model

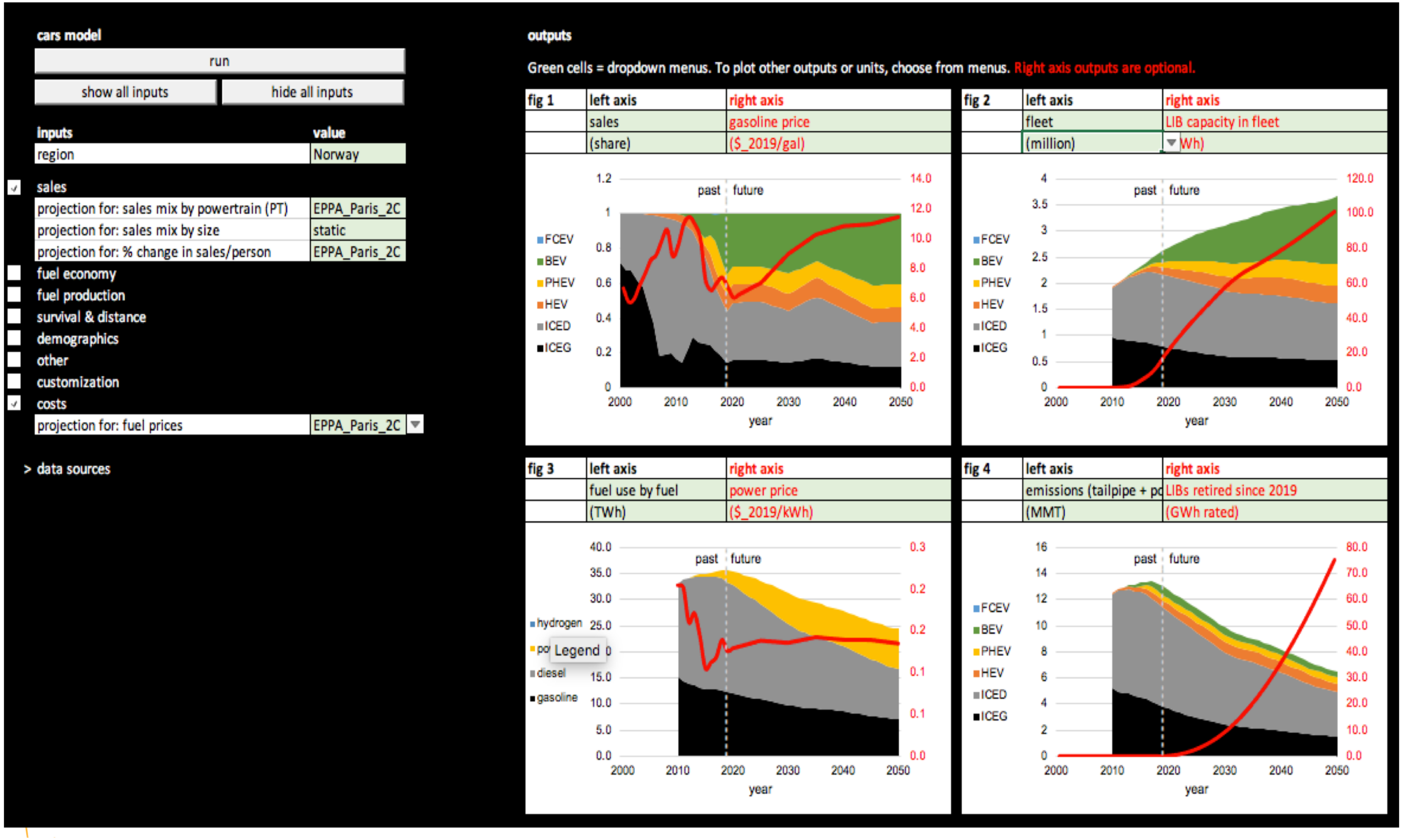
- **Capabilities**
  - Fast validated projection of fleet outputs: fleet size, fuel use, power use, battery demand, battery scrappage, emissions, and more,
  - Given different inputs of technology sales shares, fuel economy, and more (more *will* include fuel, car, and battery prices).

- **Potential users**
  - Anyone (policymakers, regulators, researchers, etc.) aiming to quickly estimate fleet fuel & emissions given different technology, price, and policy evolutions.

EPPA's Paris forever



EPPA's Paris 2C



EPPA’s Accelerate

Key Takeaways

- Understanding the evolving energy system requires new analytical capabilities that allow:
  - Exploration of emission reduction options
  - Identifying new business opportunities
- A multi-platform approach, illustrated by connecting the SESAME and EPPA models, allows integration of various levels of temporal, technological, and geospatial resolution.
  - Climate change, macroeconomics, policy scenarios, land-use impacts, etc.
- Performing technology and system scenario analysis enables accurate understanding of implications of changes in one part of the energy sector on other parts.
- Identification of best pathways to meeting climate change goals set locally and matched to regional resources is important.
  - Case studies on Norway, Singapore, and Germany demonstrate the vast difference in solution space.
  - Accurate global coverage requires close collaboration with local partners.

Thank you

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