EnergyPATHWAYS

As jurisdictions become more serious about their climate reduction goals, the imperative of an integrated approach to energy system planning is becoming clear. This is true both geographically, as the idea of appropriate "boundary conditions" in an analysis become ever blurred, but also sectorally, as emissions limits and resource allocation constraints are no longer siloed. Combine this imperative with the need to be able to represent systems that are not incrementally different from today, but instead represent a fundamental transformation to the way we produce, deliver, convert, and use energy, and you arrive at the challenge facing traditional analytical approaches when applied to the problem of energy system decarbonization.

EnergyPATHWAYS[1] (EP) is a bottom-up energy sector model with stock-level accounting of all energy infrastructure. EP was specifically built to explore a range of potential energy system transformations, and to this end, the model leaves most energy system decisions to the user. Thus, it is appropriate to think of EP as a complex accounting system or simulation model that keeps track of and determines the implications of detailed user scenario decisions. EP is the offspring of an analytical approach that has already proven to be a successful strategy to dramatically change the climate policy discussion at the global, national, and subnational levels. The basic insight is that climate policy was stuck in the realm of short-term, incremental changes discussed in abstract and academic terms, and that this failure was reinforced by the analysis and modeling approaches used. The pathways strategy was to force the policy and business worlds to address, head on, the reality that achieving greenhouse gas targets requires transformation, not incrementalism; that only a long-term perspective on the kind of infrastructure and technology changes required can prevent short-term investments that result in high-emissions lock-in; and that only an analysis that moves past the abstract focus on tons of CO2 along an emissions trajectory to a focus on the energy supply and end use equipment that produces the CO2 would speak to practical decision-makers in the regulatory, business, and investment worlds.

The value of modeling these transformation scenarios is in building a cohesive, internally consistent story with the granularity to engage all parties. Too often we jump straight to mechanisms for achieving climate mitigation (Ex. carbon price) without paying attention to what exactly these policies need to achieve. EP is not a forecasting tool, but instead uses a backcasting approach–starting first with a goal and then working to demonstrate what physical infrastructure changes are required to reach that goal and when those changes must happen. This scenario approach allows the model to easily perform "what if" analysis and to reflect the underlying physics of our energy system with sufficient granularity for effective communication, both with outside stakeholders and other modeling frameworks.

Broadly speaking, EP can be divided into a demand side and supply side, the former calculating energy demanded (E.g. kWh electricity and MMBtu natural gas) by different services (E.g. water heating and passenger vehicle travel), the later determining how each energy demand is met (E.g. natural gas extraction, power plants, transmission wires, and gas pipelines).

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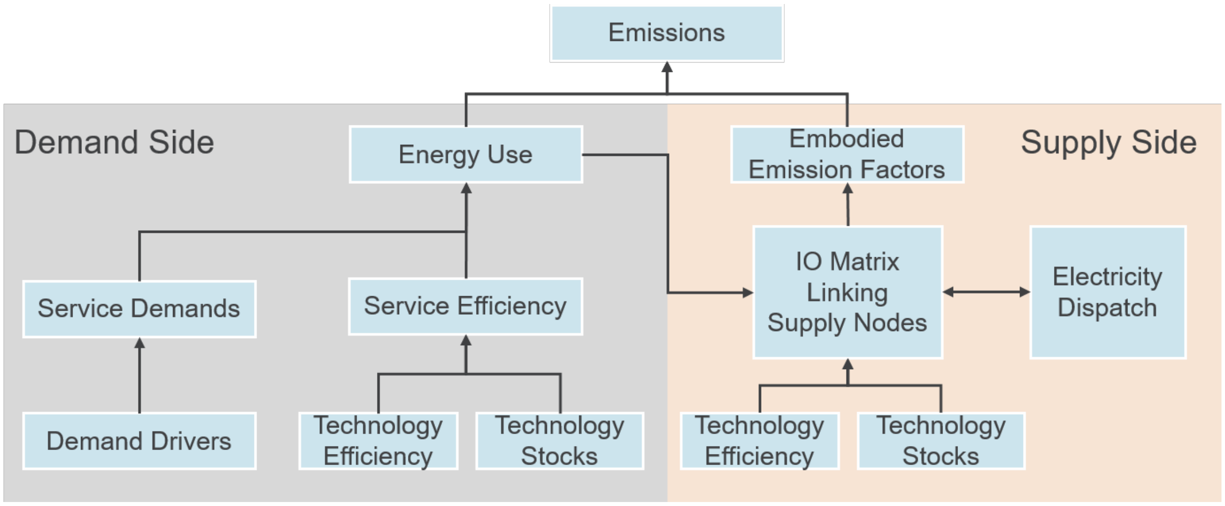
[1] EnergyPATHWAYS is an open-source modeling framework maintained by Evolved Energy Research. Databases used in analyses conducted with the EnergyPATHWAYS source code can public or maintained as proprietary. More detail can be found here: https://github.com/energyPATHWAYS/energyPATHWAYS.

MODEL FLOW DIAGRAM



Beginning on the demand side, the model starts with a set of inputs we call demand drivers. These are variables such as population or the value of industrial shipments and can be thought of as the skeleton upon which the rest of the model calculations depend. Ideally demand driver projections for future years are given, but if only historical data is available, EP will use different regression techniques to project each variable across all model years. Demand drivers are the basis for forecasting future demand for energy services. For example, if calculating the weight of laundry washed in residential households annually, a 10% increase in the demand driver, number of households, will result in a similar increase in the service demand, weight of laundry. Along with service demand, technology stocks that satisfy each service demand are tracked and projected into the future. The composition of the stock along with the efficiency of each stock type for providing services is referred to as the service efficiency, fuel economy being a classic example. Total energy demand can be calculated by dividing service demand by service efficiency and summing across each service demand category, referred to in the model as demand subsectors. The demanded energy will be in one of many different fuel types (E.g. electricity or natural gas) depending on the technologies deployed and will be specific to a geography, customer category, and even time slice, as is the case with electricity.

Once energy use is calculated, the supply-side calculations of the EP model begin. Mathematically, supply side calculations are done with an energy input-output matrix that connects the flows of energy between supply nodes that produce or deliver energy. Input-output tables are frequently used by economists and in life-cycle assessment (LCA) work, and fundamentally calculations in EP are no different, though with several unique characteristics. First, the supply-side of the EP model proceeds one year at a time and the coefficients in the input-output matrix are updated annually as parameters in each supply node change. Second, in each calculation year, a detailed electricity dispatch is used to inform how much of each supply node goes into producing one unit of electricity (e.g. how much coal vs. gas) and how much new generation, transmission, and distribution capacity is needed for a reliable system. The inputs for electricity dispatch are derived from the rest of the supply side (e.g. heat rates of different power plants) and from the demand-side where hourly 8760 electricity profiles are produced. With the updated coefficients from the electricity dispatch and change in supply technology stocks, emissions factors from each fuel type by location are calculated and combined with final energy demand to estimate emissions for future years.

Key Features

The features below represent some of the most important aspects of EP in its ability to represent the energy systems of the future.

Energy Demand Decomposition. Traditional load forecast approaches rely on regression-based approaches that use historical data to project future demand growth. Under scenarios of extreme energy efficiency or electrification, such approaches break down because no historical data is available to adequately train predictive models. Instead, EP projects load from first principles "bottom-up", either inputting or deriving granular estimates of energy service demand by end-use (i.e. kWh of space heating consumption per square meter of multi-family homes in a Swedish state) and applying the changing characteristics of equipment stocks (fuel type, efficiency, etc.) to project energy demand into the future. This also allows EP to conduct scenario analysis on each component part of the demand for energy and to examine different strategies like technology efficiency, behavioral change, conservation, early equipment retirement, etc.

Stock Rollover. We have advanced stock rollover functionality to allow for examination of a variety of end-use equipment change scenarios. We allow for induced early retirement, the specification of future equipment stock targets (i.e. 1.5 million EVs in 2030); equipment sales targets (.5 million EVs in 2025); and even the dynamic calculation of equipment stock needs based on anticipated utilization (ex. The reduction of on-road vehicles due to the introduction of high-utilization autonomous EVs). We leverage these features extensively to represent large-scale transformation of both supply and demand-side equipment stocks.

Input Flexibility. Our algorithms for cohering large sets of messy data are extremely useful in rapidly prototyping energy systems. The framework is extremely configurable and geographically flexible, allowing for representation of systems from state and utility service territories up to country and regional-level analyses with a single user input. It also utilizes advanced data mapping functions to intelligently combine datasets with different levels of aggregation.

Electricity Dispatch. EP includes a best-in-class electricity dispatch model when compared to other economy-wide energy system models. Recognizing the importance of temporal granularity in high renewable scenarios, we model the electricity system on an 8760 basis complete with distribution feeder and inter-regional transmission representations as well as algorithms for short and long-duration bulk electric storage, distributed storage, power-to-gas and other electric fuel production, flexible end-use loads like water heaters and EVs, and must-run and flexible thermal generators like nuclear facilities or CCGTs with dynamically scheduled maintenance and forced-outage parameters. We also endogenously calculate the evolution of load shapes, calculating the temporal impacts to a base-year load shape of electrification or efficiency on an end-use level. This allows us to show the impacts of large-scale electrification of space heating or vehicles.

Accounting Framework. EP uses an Input-Output Model architecture to allow for sophisticated allocation of both costs and emissions all the way from primary energy down to final consumption. For example, if desired, EP could calculate what portion of greenhouse gas emissions in a 2025 vintage EV sold in France are coming from the dispatch of coal power plants in Germany.

Example EnergyPATHWAYS Applications

Deep Decarbonization Analyses. EP has been utilized to model greenhouse gas targets in a variety of North American jurisdictions. These analyses have been conducted at the level of country, regional, state, and utility service territory.

Marginal Cost/Emissions Impacts. EP has been utilized to understand the marginal impacts of actions along trajectories of energy system transformation. This functionality can be used in the production of marginal greenhouse gas abatement curves as well as to understand the marginal impacts of energy sector activities like flexible load or energy efficiency.

Integrated Resource Planning (IRP). EP provides a supplementary tool for utilities engaged in integrated resource planning. EP can assess the impacts to a utility of expanded electrification in buildings, industry and transportation along with other new loads like electric fuel production.

Boundary conditions for Sectoral Modeling. EP can provide necessary context for detailed sectoral models investigating energy system transformation. Questions such as: how does the future load shape change? How much biomass is available for industry? What emissions factors should be assumed for electrified vehicles in future years? Answering each in the absence of a cohesive framework is difficult and can lead to inconsistencies in analysis. For this reason, EP is often used to provide detailed inputs to other energy models.