Appendix A. The Guidehouse Low Carbon Pathways Model Methodology

Governments, utilities, and commercial entities around the world are setting ambitious climate and energy targets, towards achieving a decarbonized future. However, due to the myriad decisions involved in this energy system transition, the best pathways to achieve goals are often unclear. Guidehouse's proprietary Low Carbon Pathways (LCP) model focuses on investigating different ways that regions may decarbonize energy systems, using an integrated capacity expansion and dispatch optimization model. The model facilitates critical decision-making by facilitating analysis of different potential pathways.

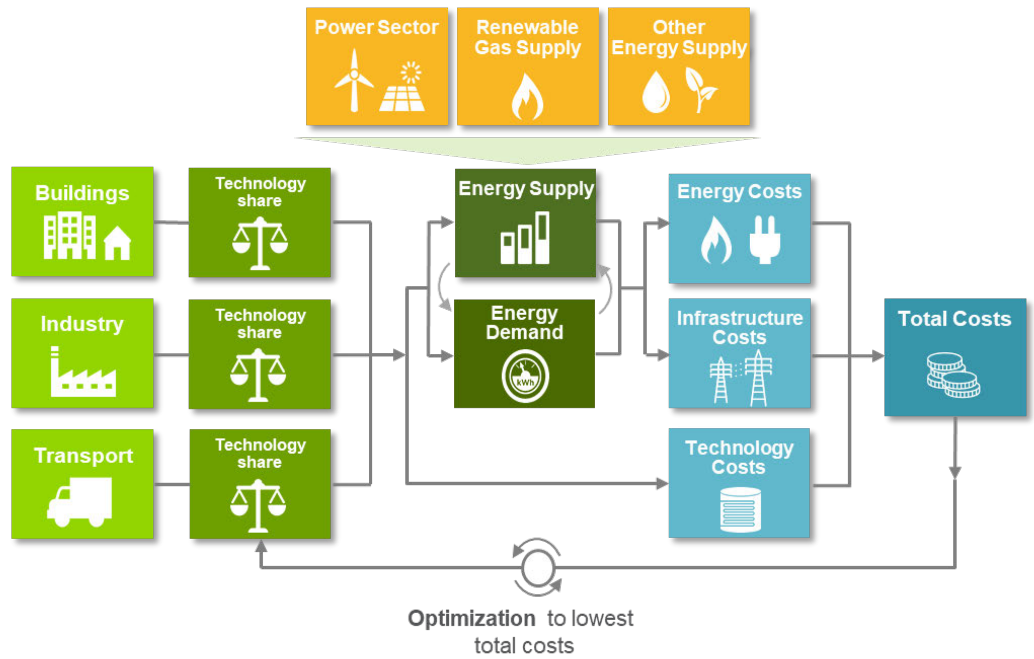
LCP leverages optimization techniques to identify the lowest total system cost pathway to achieve decarbonization targets in different scenarios:

- Within a specified time frame;
- Using a given set of technologies; and
- Under a set of constraints, both at the energy system level (e.g., the buildout and availability of supply, the development of interconnections) as well as operational, individual technology level (e.g., the operation of power generation plants).

The LCP model illustrated in Figure A-1, uses an integrated approach across different energy carriers to determine the lowest cost pathway to achieve a given scenario. Important features include:

1. Integrates decisions regarding both how much of a technology to deploy each year and how to dispatch that technology on an hourly basis.
2. Captures interactions between energy sub-systems, such as interactions between the electricity, natural gas, and hydrogen systems.
3. Uses representative days and peak days to reflect the seasonal variability of electricity and gas demand loads and supply resources.
4. Simulates a given energy system, subdivided into one or more primary regions, as well as one or more secondary neighboring regions.

Figure A-1. Low Carbon Pathways Model Overview



A.1 Model Inputs

Defined scenarios drive runs of the LCP model. A scenario consists of scope and resolution of geography, time period, and defined decarbonization targets (e.g., achieving net-zero for specific regions over 2030-2050). The scenario also represents a particular pathway to achieve targets, based on parameters such as:

- Existing and planned generation, storage, and transmission capacities over the time period
- Potential supply technologies that could be deployed, including technological characteristics and associated costs
- Forecasted demand for hydrogen, electricity, and natural gas (e.g., in different sectors) – this is accomplished exogenously to the LCP model itself.
- Potentials for renewable energy resources
- Fuel and emissions price assumptions

Example scenarios could compare achieving targets using a full-electrification pathway with an integrated pathway involving a mix of electricity, hydrogen, and renewable natural gas. Table A-1 describes the inputs that define a scenario. Scenarios may be defined by a subset of these inputs depending on the requirements of a particular study.

Table A-1. Example Input Data and Assumptions Required for LCP Modelling

Category	Input Data
General	**Economic parameters** (e.g., WACC)
Model Dimensions	**Temporal** (Season, representative days, temporal granularity) **Geographic** (Primary and neighbouring regions)
Emissions	Emissions target, carbon prices, offset prices and availability, emissions intensities for supply technologies
Demand	**Reference Case forecast of demand (e.g., 2020-2050)** • Electricity, methane, and hydrogen demand
Demand	**Hourly demand profiles by sector & network load profiles** • Hourly profiles for each representative day (e.g., each season and a winter and/or summer-peak)
Supply	**Existing supply capacity** • Current electricity supply mix and gas supply mix (e.g., imports, domestic biogas production via anaerobic digestion, etc.)
Supply	**Planned changes to system capacity (e.g., in 2030, 2040, and 2050)** • Planned capacity additions and planned capacity retirements
Supply	**Input fuel types and prices**
Supply	**Maximum fuel type supply potentials (or minimum supply), e.g.:** • Define max limit on RNG supply via anaerobic digestion and biomass gasification • Define max limit on blue and green hydrogen supply • Define max limit on gas storage capacity (salt caverns, aquifers, etc.)
Supply	**Techno-economic parameters for supply technologies considered, e.g.,** • Electricity: Solar, wind, hydrogen- and natural gas-fired CCGT / OCGT, battery storage, etc. • Hydrogen: Blue H2 (SMR + CCS) and green H2 (dedicated vs. curtailed renewables), H2 storage (salt caverns, aquifers, etc.) • Methane: Anaerobic digestion, biomass gasification
Infrastructure	**Existing (e.g., 2020) and planned (e.g., 2030, 2040, 2050) interconnection capacities** • Capacities for energy exchange between the primary region and connected neighboring regions
Infrastructure	**Cost parameters for new electric transmission lines** • Overhead AC, Underground/Overhead HVDC
Infrastructure	**Cost parameters for new and repurposed methane and hydrogen** transmission pipelines
End Users	**Cost of end user retrofits and equipment replacement, e.g.,** • Cost of weatherization and deep building retrofits • Total installed cost of heating equipment (e.g., whole-building electric heat pumps, dual fuel systems, and gas heat pumps) • Total installed cost of other relevant appliances (water heaters, cooktops, etc.)

A.2 Model Optimization

Fundamentally, LCP is an optimization model, comprising an objective function, decision variables (DVs), and constraints. Figure A-2 provides an illustrative example of a generic optimization for two decision variables and three constraints, where the model attempts to determine a single point in the feasible region that minimizes the objective function.

Figure A-2. Illustrative Depiction of Optimization

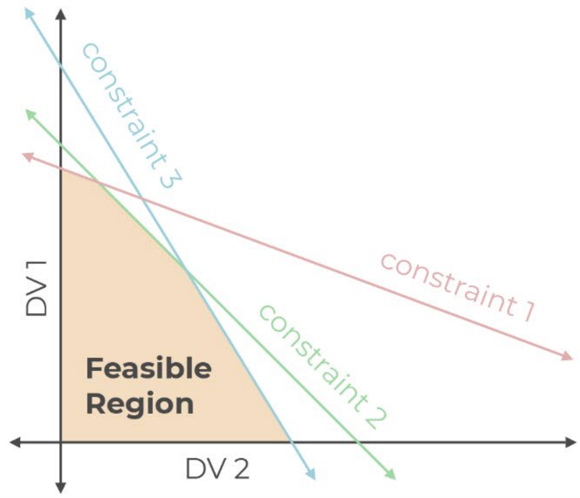
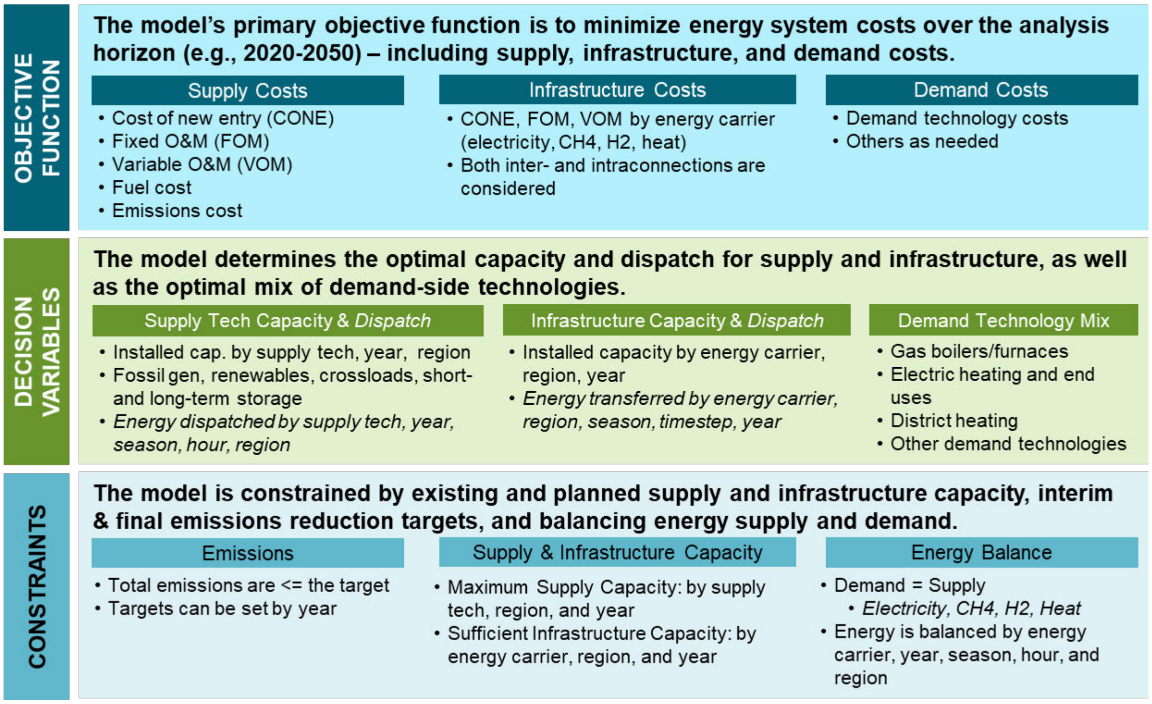


Figure A-3 describes the objective function, DVs, and constraints for the LCP model in more detail. From a whole-system, central planning perspective, LCP minimizes the net present value of total system cost – capital expenditures (CAPEX) as well as fixed and variable operational expenditures (OPEX) – over the specified time period (e.g., 2030-2050).

Figure A-3. LCP Model Objective Function, Decision Variables, and Constraints



A.2.1 Dimensionality

The model currently uses the following dimensions:

- **Simulation Year:** Calendar years considered, e.g., 2020, 2030, 2040, 2050
- **Season:** Seasons to represent in the model, e.g., Summer, Summer Peak, Winter, Winter Peak, Fall, Spring
- **Timestep:** The temporal resolution of demand in the model, e.g., hourly, at hours 1, 2, 3, …, and 24
- **Subregion:** Regions to model e.g., an entire province/state or subregions therein as well as neighbouring provinces/states.
- **Supply Technology:** energy supply technologies considered, e.g., electric generation from nuclear, coal, and solar resources, and hydrogen generation from SMR and electrolyzer resources
- **Infrastructure Technology:** Means of transporting energy considered, e.g., Wire, Pipe, Trucked Hydrogen
- **Fuel Type:** Energy carriers considered e.g., Electricity, Heat, Hydrogen, Methane

A.2.2 Supply Technology Definitions

This section provides some definitions regarding supply technologies within the LCP model.

Generation Technologies

Technologies defined as “Generation” use imported fuels with defined costs and availability, if applicable, and capacity factors to account for total limits on resource availability and seasonal variation in that availability. For example, an onshore wind power plant has no associated fuel costs, but has a capacity factor that depends on both Timestep and Season to account for patterns in wind direction and speed.

Crossload Technologies

Technologies defined as “Crossload” use a modeled Fuel Type to produce a different modeled Fuel Type. For example, electrolyzers may use electricity (produced by other technologies in the model) to produce hydrogen (which is then used to meet end use demand). Natural gas and hydrogen turbines use a gaseous fuel to produce electricity, depending on the amount of gaseous fuel that can be produced in or imported to the region.

Storage Technologies

Storage technologies have the same input fuel and output fuel and are able to store energy hourly and/or seasonally. The capacity of a storage technology refers to the amount of energy the technology can charge or discharge in a single timestep. For example, an electric battery that can dispatch 20 kW and has a 3 hour storage duration would have a capacity of 20 kW and a storage capacity of 60 kWh.

Some storage technologies are eligible for carryover storage, which allows them to use energy stored in the previous seasons for other seasons. For example, natural gas storage which typically fills in the summer and empties in the winter.

Technology Groups

Supply technology groups model supply technologies that are dependent on the capacity or dispatch of another supply technology, such as H2 enriched natural gas or an open cycle gas turbine that can use hydrogen or natural gas as an input fuel. Within a technology group, one is considered a primary technology (the one mainly used) and the other is considered secondary.

Import Technologies

These technologies represent imported energy separately from defined infrastructure connections between neighbouring Subregions (i.e. they are a different way of characterizing imported energy). When defining import technologies, the cost can be characterized as a fuel cost per unit of energy and/or a CAPEX and OPEX of building and operating the infrastructure needed to deliver the energy. For example, methane imports can be defined as an import technology using the price of natural gas at the point of reception in the associated Subregion.

Retrofitted Technologies

Supply technologies and infrastructure technologies can both be modeled as “retrofits” of existing original technologies. The “original tech” is the technology that’s being replaced and the “replacement tech” is the new technology that’s being brought online. CAPEX of retrofit technologies may be substantially lower than the installation of new resources, depending on the retrofit. Similar to new installs, the total cost of production for retrofit resources accounts for the capital cost of installing the resource and the operating cost of using the resource to produce energy. The capacity of the replacement technology is limited by the existing capacity of the original technology subject to a defined limit.

A.2.3 Decision Variables

DVs represent the unknowns the optimizer will solve, for example, the amount of energy dispatched from a specific nuclear plant in the summer of 2050. In the model, all decisions are combined into a vector of variables for which the model ultimately finds a cost-optimized solution, $DV_1, DV_2, \ldots, DV_n$. The full decision vector represents how an energy system would change (e.g., what is constructed) and how it is dispatched over the analysis timeframe.

The number of DVs will vary based on how the model is configured, but comprise the following categories:

1. **Dispatch**
   The modeled energy dispatched by each Supply Technology in each Timestep, Season, Simulation Year, and Subregion. This decision variable captures the dispatch of generation facilities, storage technologies, crossload technologies, import, and export technologies.
2. **Storage**
   The modeled amount of energy charging for both short and long-term storage technologies (i.e., batteries, natural gas storage, hydrogen storage) in each Timestep, Season, Simulation Year, and Subregion.
3. **Carryover**
   For relevant technologies, the modeled amount of stored energy to carry over from one Season or Simulation Year to the next by Subregion. Specifically, this decision variable represents the level of storage that the simulation starts with in each Season and Simulation Year. This is particularly relevant to long-term seasonal storage such as underground gas storage or a hydro reservoir.
4. **Supply Capacity**
   The modeled new capacity of each Supply Technology installed in each Simulation Year and Subregion. This sets the maximum energy output in each timestep (constraint described below). Includes generation facilities, storage technologies, and crossload technologies.
5. **Intra/Interconnection Capacity**
   The modeled new capacity installed of each Infrastructure Technology connecting two Subregions together (“interconnection”) and within a Subregion (“intraconnection”) for each Simulation year and Subregion. This sets the maximum amount of energy that can be transmitted across that infrastructure in each Timestep.
6. **Intra/Interconnection Dispatch**
   The modeled amount of energy transmitted from one Subregion to another (“inter-”) or distributed within a Subregion (“intra-”) in each Timestep, Season, and Simulation Year.
7. **Carbon Offset**
   The modeled quantity of offsets used to reach emission targets, specified system-wide (across all Subregions) for each Simulation Year.
8. **Supply Retrofits**
   The modeled retrofitted capacity of each Supply Technology (if eligible to be retrofitted) in each Simulation Year and Subregion. This keeps track of how much of the original supply technology capacity has been replaced by a replacement technology.

A.2.4 Objective Function

LCP's core objective is to minimize the present value of total system costs over the analysis horizon. To setup the objective function, the model generates a cost for each DV. That is, for a given a decision vector, $DV_1, DV_2, \dots, DV_n$, the model generates an associated cost objective vector, $Cost_1, Cost_2, \dots, Cost_n$, such that the objective function becomes:

$$Cost_1 DV_1 + Cost_2 DV_2 + \cdots + Cost_n DV_n = Total\ Cost$$

The model seeks to minimize Total Cost and leverages a commercially available solver, Gurobi. Since there are many dimensions to the model including time, the cost function for each decision variable must account for factors such as the time value of money, technology lifetimes, and the salvage value of resources at the end of the study period.

A.2.5 Constraints

The LCP model imposes limitations on the optimization of decision variables when determining the solution for a given scenario. In other words, the model determines the set of decision variables that minimizes the objective function subject to a set of constraints. The constraints defined in the model comprise the following categories:

1. **Energy Balance** – energy balance is split into two distinct balances (one at generation and one at end use) to enable flexibility such as modeling multiple intraconnection technologies (e.g., trucks vs. pipeline) and multiple crossloads at the end use (e.g., heat pump converting electricity into heat vs. furnace converting natural gas into heat)

   [redacted]

   [redacted]

2. **Dispatch** – constraints on dispatch could require that dispatch is less than capacity (supply technologies), meet minimum dispatch, be less than capacity (infrastructure), have regional constraints on percent of energy imported, constrain firm capacity, or limit one-way capacity.

   [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3. Capacity -

[redacted]

[redacted]

[redacted]

[redacted]

4. **Emissions** – Emissions constraints involve overall emissions targets in each year, as well as limits on carbon offsets.

[redacted]

5. **Storage** – The storage constraints pertain to storage technologies (e.g., batteries, natural gas storage, hydrogen storage), and are constrained in terms of their charge and dispatch levels

[redacted]

[redacted]

6. **Ramping** – Supply technologies can be constrained in terms of how fast they can be ramped up or down.

[redacted]

[redacted]

7. **Technology Groups** –The model includes some possible constraints regarding how technology groups are treated, including that their capacities must be equal to maintain linearity in the optimization problem, and that the secondary technology must be dispatched at a specified proportion of the primary technology. For example, this constraint may be used to model hydrogen blended into natural gas at 6% energy content.

[redacted]

[redacted]

[redacted]

8. **Annual Fuel Usage** – Annual usage of input fuels can be individually constrained at a maximum or minimum.

[redacted]

[redacted]

A.3 Model Outputs

Successful execution of the model (i.e., finding a feasible solution) produces a solution vector (i.e., optimal values for the decision vector, $DV_1, DV_2, \ldots, DV_n$). The model processes the solution to output important details, such as:

- **Required investments in new generation and storage capacity** – e.g., solar, wind, electrolyzers, and hydrogen storage
- **System operation** – e.g., system dispatch, energy flows between regions, storage levels, and curtailment
- **System costs** – e.g., CAPEX, OPEX, fuel costs, and CO_2 emissions costs
- **CO_2 emissions incurred throughout the study period** – e.g. emissions resulting from the dispatch of natural gas plants, or losses in transport

A.4 Model Limitations

The LCP model has been designed with the intent of being as comprehensive as is practical within the scope of its intended use as a tool to explore different scenarios of a decarbonized future. The model does currently have limitations in its capabilities and application, and some important ones include:

- While the model calculates total supply of energy from different sources (e.g., MWh from onshore wind) and total production cost for supply technologies (e.g., total CAPEX and OPEX of onshore wind), the model does not attempt to calculate retail or wholesale cost of energy of different energy sources (e.g., $/kWh). This is a deliberate design choice. The future cost of energy will depend on factors that are not forecast by the model, such as cost of financing, tax rates, depreciation schedules and other factors. Additionally, energy rates could depend on future policy initiatives to incentivize particular technologies or to promote cost socialization. The goal of the model is to determine the approach to energy supply that will result in the least cost outcome from an economy-wide perspective.
- The LCP model optimizes supply-side resources but does not currently optimize demand-side technologies. For scenario-based analyses, demand-side technologies (e.g., heat electrification, efficiency improvements, fuel substitutions, etc.) are set by the scenario definitions. The impact of demand-side technologies on the annual and hourly demand for different energy types is calculated exogenously to the LCP model. For example, a scenario may define the adoption curve and future saturations of different heat pump technologies (e.g., air-source, ground-source, and gas heat pumps) and the LCP model's optimization function is not designed to alter these scenario-defining characteristics.
- The LCP model does not currently deploy demand response technologies as a supply resource. The model takes hourly demand profiles as an input and does not include technologies that could in effect shift the hourly demand profiles specified for individual scenarios. If demand response approaches are to be considered in a scenario, they must be specified in the upstream calculations that produce the hourly demand profiles that are taken as an input to the LCP model.
- The LCP model is not configured to model exact transmission and distribution systems (i.e. every substation). These systems are typically simplified to represent capacity connections between and within Subregions.