HYDRO QUEBEC RESEARCH INSTITUTE (IREQ)

AN ENERGY TRANSITION TOOL

REPORT

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# Modeling & Propositions

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# 1 Energy System Modeling

## 1.1 ECONOMY ENERGY MODELS

Energy modeling has increased in importance as the need for climate change mitigation has grown in importance. The energy supply sector is the largest contributor to global greenhouse gas emissions [1]. The Intergovernmental Panel on Climate Change (IPCC) reports that climate change mitigation will require a fundamental transformation of the energy supply system, including the substitution of unabated (not captured by CCS) fossil fuel conversion technologies by low-GHG alternatives [1].

Energy modeling or energy system modeling is the process of building computer models of energy systems in order to analyze them. Such models often employ scenario analysis to investigate different assumptions about the technical and economic conditions at play. Many modelling is done by coins and it is to show that a lot is made. Outputs may include the system feasibility, greenhouse gas emissions, cumulative financial costs, natural resource use, and energy efficiency of the system under investigation. A wide range of techniques are employed, ranging from broadly economic to broadly engineering. Mathematical optimization is often used to determine the least-cost in some sense. Models can be international, regional, national, municipal, or stand-alone in scope. Governments maintain national energy models for energy policy development.

As an energy balance provides a simple representation of an energy system, the energy accounting approach is one of the frameworks used in energy system analysis. Hoffman and Wood (1976) describe the initial efforts in this area and suggest that this consistent and comprehensive approach has been used since 1950s in the US. The accounting framework of analysis is very popular even today and models such as LEAP or MEDEE/ MAED essentially employ this framework. A natural extension of the energy balance framework was to use a network description of the energy system to represent energy flows. This development took place in the early 1970s and has found extensive use until now. The reference energy system (RES) captures all the activities involved in the production, conversion and utilisation of energy in detail by taking the technological characteristics of the system into account. This approach allows incorporation of existing as well as future technologies in the system and facilitates analysis of economic, resource and environmental impacts of alternative development paths. This approach was developed by Hoffman [Hoffman and Wood, 1976] and has set a new tradition in energy system modelling.

### 1.1.1 Top-down approach

Top-down energy models focus on the macro-economy and balance supply and demand across all economic sectors. These models use a stylistic representation of technologies, which change over time due to elasticity (responsiveness to price) assumptions.

### 1.1.2 Bottom-up approach

Bottom-up energy models contain richer characterizations of technology cost and performance, and technology change depends on the availability and ability of technologies to substitute for each other.

One approach is not necessarily superior to the other but depends on the type of research question being asked. But, we believe that bottom-up energy models, which track physical flows of energy and their infrastructure, are the best suited to answer the question “How do we deeply decarbonize the energy system?”

## 1.2 Bottom up vs Top-Down

Table.1, shows a comparison between two economic methods:

Table 1: COMPARISON BETWEEN METHODS

| APPROACH | |
|---|---|
| Top-Down approach | Bottom-up approach |
| use an "economic approach" | use an "engineering approach" |
| give pessimistic estimates on "best" performance | give optimistic estimates on "best" performance |
| can not explicitly represent technologies | allow for detailed description of technologies |
| reflect available technologies adopted by the market | reflect technical potential |
| the "most efficient" technologies are given by the production frontier (which is set by market behavior) | efficient technologies can lie beyond the economic production frontier suggested by market behavior |
| use aggregated data for predicting purposes | use disaggregated data for exploring purposes |
| are based on observed market behavior | are independent of observed market behavior |
| disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements | disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements |
| determine energy demand through aggregate economic indices (GNP, price elasticities), but vary in addressing energy supply | represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption |
| endogenize behavioral relationships | assess costs of technological options directly |
| assumes there are no discontinuities in historical trends | assumes interactions between energy sector and other sectors is negligible |

The distinction between top-down and bottom-up can generally be typified as the distinction between aggregated and disaggregated models respectively, or as the distinction between models with a maximum degree of endogenized behavior and models with a minimum degree. Furthermore, (early) topdown models are generally used for prediction purposes, while bottom-up models are mainly used for exploring purposes. In the following two models for energy system modelling are compared for better representation of applied energy approach in the proposed model.

## 1.3 CanESS

The CanESS model provides economic and socioeconomic plans for Canada, supporting energy system definitions, validating parameters to be used, and performing extensive background testing and verification to ensure that the results from the project are consistent and credible[2].

### 1.3.1 Characteristics

The Canadian Energy Systems Simulator (CanESS), developed by whatIf? Technologies Inc., is an integrated, multi-fuel, multi-sector, provincially-disaggregated energy systems model for Canada. CanESS :

- Enables **Bottom-up accounting for energy supply and demand**, including

  - energy feedstocks (e.g. coal, oil, gas)
  - energy consuming stocks (e.g. vehicles, appliances, dwellings)
  - and all intermediate energy flows

- Focuses on **coherency** – on creating scenarios assuring consistency among
  - the population
  - level of economic activity
  - the services required by the population
  - the energy system
  - the emissions of greenhouse gases
  - criteria air contaminants

- It assures **coherency** both *over time and within time periods* through
  - the use of stock-flow accounting rules
  - vintaged stocks and life tables
  - the use of stock-flow accounting rules
  - supply/disposition balances for fuels and feedstocks
  - the explicit representation of energy transformations

- CanESS is calibrated over historical time from 1978 to the present in one year steps.

### 1.3.2 Applications

Here is a selection of issues which CanESS can address:

- fuel switching
- national and provincial carbon budgets
- energy efficiency potential
- building envelope retrofit impacts
- technology assessment
- integration of intermittent renewable energy sources
- international and interprovincial energy trade
- electricity generation capacity planning and “greening” the grid
- energy system costs
- carbon intensity of oil sands production
- travel behaviour change impacts
- vehicle fuel standards impacts
- electric, hydrogen & renewable-fuel vehicle energy analysis

- freight transportation fuel options
- electricity demand response
- combined heat and power (CHP)
- multi-generational energy infrastructure planning
- sensitivity of energy demand to variation of population and economic projections
- shifting lifestyles and energy use linkage

### 1.3.3 Drivers for Demand Forecast

- **Demographics**:

  CanESS contains a population cohort-survival model which stratifies the population by single year of

  - age
  - gender
  - geographic region

  projects in 1-year time steps. The model accounts for

  - births
  - deaths
  - international and interprovincial migration flows

  Families by

  - age class
  - size
  - structure

  are projected from the population via family formation rates.

- **Macro economy**:

  Table 2 below shows the macroeconomic drivers that CanESS produces and the level of detail for those variables

### 1.3.4 Final Demand Sectors

CanESS considers different sectors for demand side such as:

#### 1.3.4.1 Residential End-use

Figure 1 shows the components of residential end-use sector.

Table 2: Macro economy variables Approach

| Variable | indices |
|---|---|
| GDP | Geographic region |
| Gross output | Geographic region and industrial sector |
| Gross output for sectors that use long haul freight | Geographic region |
| Gross output for sectors that use short haul freight | Geographic region |
| Gross output for sectors that use off road transportation | Geographic region |

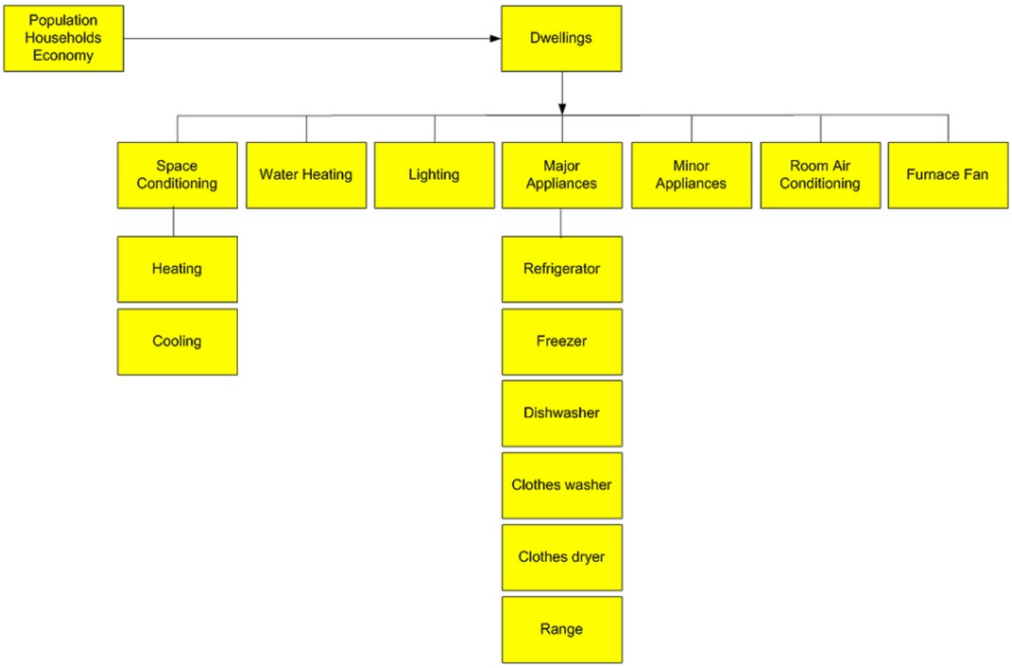

Figure 1: Residential end-use components diagram

### 1.3.4.2 Commercial End-use

The CanESS commercial model uses floor space and energy intensity parameters to derive energy use across commercial end-uses. The exception to this method is lighting, which uses a stock-based approach to calculate energy use. CanESS represents the following set of commercial building types:

- Wholesale
- Retail
- Warehouse - Transportation and Warehousing
- Cultural - Information and Cultural Industries
- Office - Finance, Retail, and Professional
- Educational - Educational Services
- Health - Health care and Social Assistance

- Recreation - Arts, Entertainment and Recreation
- Accommodation - Accommodation and Food Services
- Other - Other Services (Except Public Admin)

Figure 2 presents the diagram of commercial end-use model components.

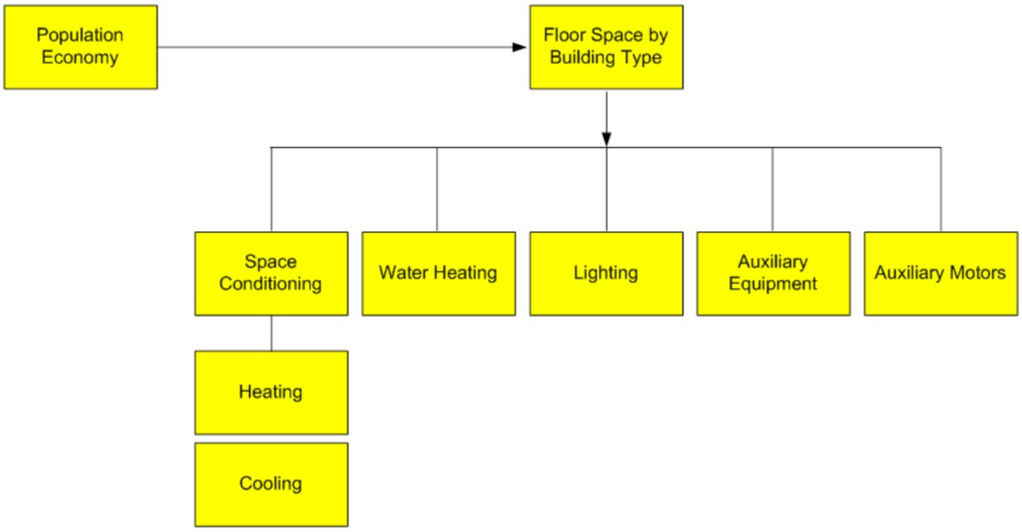

Figure 2: Commercial end-use model components diagram

#### 1.3.4.3 Transportation

The CanESS transportation model calculates energy use by vehicle kind and fuel type based on service demand and road vehicle stock for both passenger and freight transportation. Figure 3 presents an overview of the sub-sectors within the transportation model.

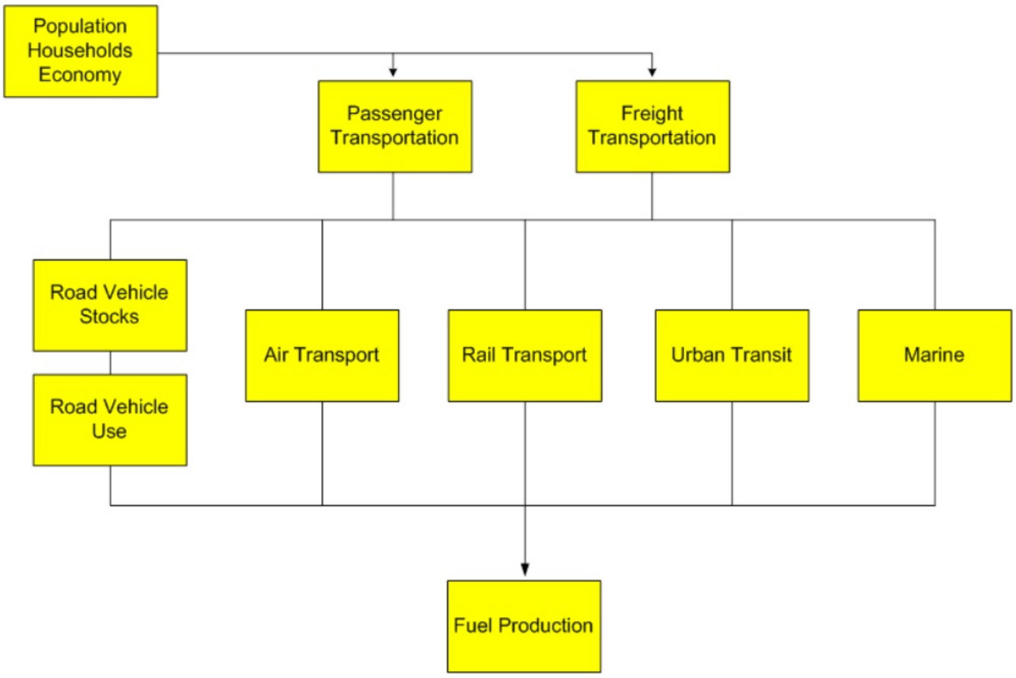

Figure 3: Transportation end-use model components diagram

The light duty vehicle power sources contained in CanESS are shown in the table below.
The light duty vehicle power sources contained in CanESS are shown in the table below.

Table 3: The light duty vehicle power source in CanESS

| Engine Type | fuel Type |
|---|---|
| Internal Combustion | Gas |
| | Gas Hybrid |
| | Diesel |
| | Diesel Hybrid |
| | Compressed Hydrogen |
| | Liquid Hydrogen |
| | Compressed Natural Gas |
| | Liquid Natural Gas |
| Fuel Cell | Gas |
| | Diesel |
| | Natural Gas |
| | Compressed Hydrogen |
| | Liquid Hydrogen |
| | Ethanol |
| Plug-in Hybrid | Gas |
| | Diesel |
| | Electricity |
| | |
| Electric | Electricity |

### 1.3.4.4 Industrial

For every industry sub-sector, CanESS obtains industrial GDP as a fraction of Canadian GDP. Figure 4, illustrates the components of industrial end-use model.

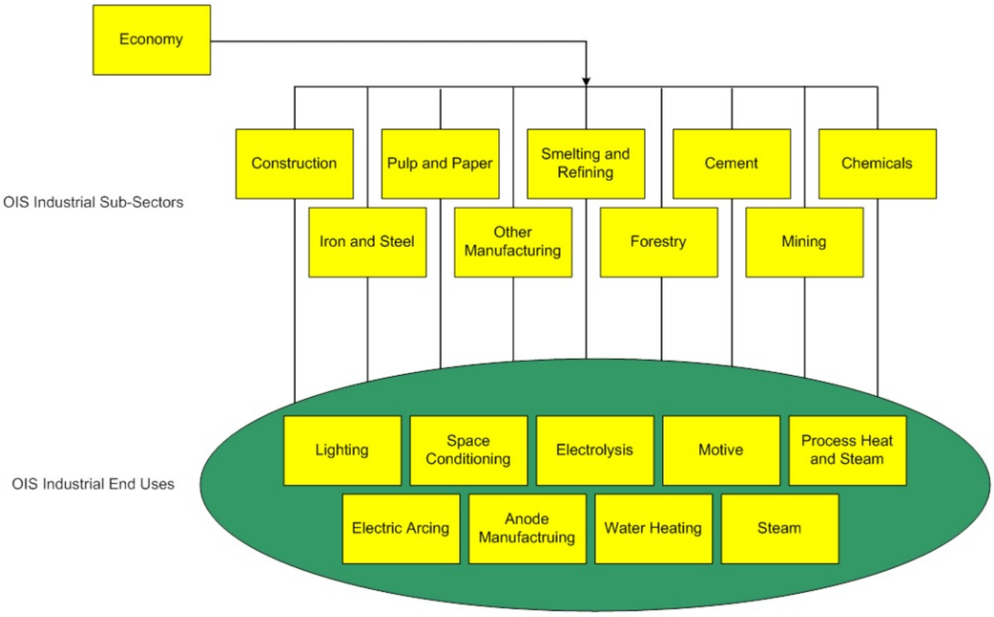

Figure 4: Industrial end-use model components diagram

#### 1.3.4.5 Summary of end-use sectors

Table 4, represents a summary for the drivers of each end-use sector.

Table 4: Summary of end-use sectors drivers

| End use type | Driver |
|---|---|
| Residential | Population, Households and Economy |
| Commercial | Population and Economy |
| Transportation | Population, Households and Economy |
| Industrial | Economy |

### 1.3.5 Energy Production

Energy supply sector of CanESS includes:

- Electricity Generation: 33 different generation technology
- Refined Petroleum Products
- Biofuels
- Other Transportation Fuels
- Hydrogen
- Liquid Natural Gas
- Steam
- Decentralized Energy :
  The model distinguishes between decentralized electricity and heat production that is biomass sourced, and decentralized energy fueled by other feedstocks.

### 1.3.6 Primary Resources

CanESS considers different resources as:

- Crude Oil
- Natural Gas
- Natural Gas Liquids
- Coal
- Uranium
- Biomass

## 1.4 EnergyPATHWAYS

EnergyPATHWAYS 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 sub-national levels [3].

### 1.4.1 Characteristics

EnergyPATHWAYS is not a forecasting tool, but instead uses a backcasting approach–starting first with a goal and then working to show what physical infrastructure changes are required to reach that goal and when those changes must happen. Other characteristics of energyPATHWAY are provided as following:

- The **bottom-up energy** model is utilized.
- Incorporates an advanced accounting framework
- EnergyPATHWAYS is a scenario planning tool which allows users to "simulate" the consequences of specific decisions as energy infrastructure evolves over time.
- The model itself is not optimization-based and embeds few decision dynamics
- It has economy wide energy models that treat electricity simplistically; and separately, it has detailed electricity sector models with no endogenous treatment of energy demand.
- Sufficient level of output granularity that can be achieved
    - annual market size and growth
    - results that are geographically relevant for their constituents
    - service demand cost and lifestyle changes
- Data Flexibility
- Comprehensive Accounting
- Hourly electricity dispatch :Optimization algorithms for:
    - electric fuel production (hydrogen electrolysis and power-to-gas )
    - short-duration energy storage,
    - long-duration energy storage
    - flexible end-use loads
- Energy system representation
    - Flexible parameterization allows for upscaling and downscaling of represented energy systems.
    - Can support regional/national/state/municipal analyses
    - Can support analyses with widely varying levels of data quality

### 1.4.2 Demand Drivers

- population
- vehicle miles traveled per capita across a long stretch of years

In this model, the total vehicle fleet size can be obtained by means of **Service Demand**. Service demand is also can be occurred by multiplying population and vehicle miles traveled per capita.

### 1.4.3 Final Demand Sector

- Commercial
- Productive (agriculture, food and kindred products, construction, paper and allied products, ...)
- Residential (water heating, space heating, lighting, cloth washing, ...)
- Transportation (medium duty trucks, buses, freight rail, ...)

### 1.4.4 Supply Node

#### 1.4.4.1 Blend

- Hydrogen
- Pipeline Gas
- Diesel
- Gasoline
- Jet Fuel
- Bulk Electricity
- LPG Feedstocks
- Steam
- Pipeline Gas
- Natural Gas
- Oil
- Thermal Dispatch
- Distributed Electricity
- Ethanol
- Coal

#### 1.4.4.2 Conversion

- Onshore Wind
- Offshore Wind
- Rooftop Solar PV
- Distribution-Sited Solar PV
- Transmission-Sited Solar PV
- Nuclear Power Plants
- Combined-Cycle Gas Turbines
- Coal Power Plants
- Combustion Turbines
- Geothermal Power Plants
- Run of River Hydroelectric Power Plants
- Dispatchable Hydroelectric Power Plants
- Hydrogen Electrolysis - Central Station
- Hydrogen Gas Reformation Central Station
- Renewable Diesel Production Facilities
- Gas Compression and Fueling Stations
- Liquefied Gas Fueling Station
- Combined Heat and Power
- Power-to-Gas Production Facilities
- BIomass Gasification Facilities
- Renewable Jet-Fuel Production Facilities
- Ethanol Production Facilities
- Demand Response
- Petroleum Refineries
- Solar - Thermal Hydrogen Production Facilities -Central Station
- Pipeline Gas Liquefaction Facilities
- Anaerobic Digesters - Lignocellulosic
- Anaerobic Digesters - Manure
- Fossil Steam Turbines

- Biomass Power Plants
- Industrial Boilers
- Fuel Cell Power Plants
- Solar Thermal Power Plants
- Biomass Boilers

#### 1.4.4.3 Delivery

- Electricity Distribution Grid
- Electricity Transmission Grid
- Gas Distribution Pipeline
- Gas Transmission Pipeline
- Hydrogen Fueling Stations
- Liquid Hydrogen Truck Delivery
- Motor Gasoline End-Use Delivery
- Diesel End-Use Delivery
- Residual Fuel-Oil End-Use Delivery
- Coal - End-Use Delivery
- Coal - Rail Delivery

#### 1.4.4.4 Import

- Uranium
- Coal
- Coke
- Refined Fossil Diesel Product
- Refined Fossil Gasoline Product
- Refined Fossil Kerosene Product
- Refined Fossil Jet Fuel Product
- Refined Fossil LPG Product
- Lubricants Product
- Petroleum Coke Product
- Other Petroleum Import
- Still Gas Product

- Residual Fossil Fuel Oil Product
- Renewable Pipeline Gas Product
- Petrochemical Feedstocks
- Ethanol Product - International
- Asphalt Product

#### 1.4.4.5 Primary

- Hydro
- Geothermal
- Coal Primary - Domestic
- Wind
- Solar
- Biomass Primary - Domestic Non-Woody Cellulosic
- Natural Gas Primary - Domestic
- Biomass Primary - Domestic Pulping Liquors
- Oil Primary - Domestic
- Biomass Primary - International
- Oil Primary - International
- Biomass Primary - Domestic Manure
- Biomass Primary - Domestic Wood
- Biomass Primary - Domestic Lipid
- Biomass Primary - Domestic Corn
- Natural Gas - International
- Uranium - Primary

#### 1.4.4.6 Storage

- Bulk Electricity Storage
- Distributed Storage

## 1.5 CanESS vs energyPATHWAY

Table 5, represents a comparison between CanESS model and energyPATHWAY model. Both models use bottom-up energy model for demand and supply sides. However, we can see more detailes for demand side in CanESS and more details for supply side in energyPATHWAY. In the view point of Demand Drivers, CanESS considers demographics' variables as well as variables of macro economy.

Table 5: COMPARISON BETWEEN CANESS AND ENERGYPATHWAY

| Section | CanESS | energyPATHWAY |
|---|---|---|
| Demand Drivers | Demographics and Macro economy | Population and vehicle miles traveled per capita |
| Demand Sectors | Residential<br>Commercial<br>Industrial<br>Transportation | Residential<br>Commercial<br>Productive<br>Transportation |
| Supply Sector | Electricity<br>Refined Petroleum<br>Biofuels<br>Other Transportation fuel<br>Hydrogen<br>Liquid Natural Gas<br>Steam<br>Decentralized Energy<br>Primary source | blend<br>Conversion<br>Delivery<br>Primary source<br>storage |
| Hourly dispatch | distributed merit order method | Optimization algorithms for electric fuel production (hydrogen electrolysis and power-to-gas); short-duration energy storage, long-duration energy storage; flexible end-use loads |
| Economic method | Bottom-up approach | Bottom-up approach |

# 2 Power System Planning Model: SWITCH

SWITCH is designed to choose optimal plans for expansion and operation of power systems **based on the hourly behavior of renewable resources, demand response, storage and conventional power plants** [4].

## 2.1 Objective Functions

The objective function power system planning model in SWITCH include [4]:

- capital costs of existing and new power plants and storage projects
- fixed operations and maintenance (O&M) costs incurred by all active power plants and storage projects
- variable costs incurred by each plant, including variable O&M costs, fuel costs to produce electricity and provide spinning reserves, and any carbon costs of greenhouse gas emissions (carbon costs are not included)
- capital costs of new and existing transmission lines and distribution infrastructure
- annual O&M costs of new and existing transmission lines and distribution infrastructure

## 2.2 Constraints

The model includes a few main sets of constraints [4]:

- 1. those that ensure that demand is satisfied
- 2. those that maintain reserves for reliability purposes
- 3. those that enforce public policy constraints (such as a cap on carbon emissions)
- 4. those that enforce resource constraints for generation projects
- 5. those that govern the installation of additional transmission and distribution capacity
- 6. those that model the operational characteristics of generation and storage projects
- 7. those that govern the dispatch of demand response

# 3 Integrating energyPATHWAY and SWITCH

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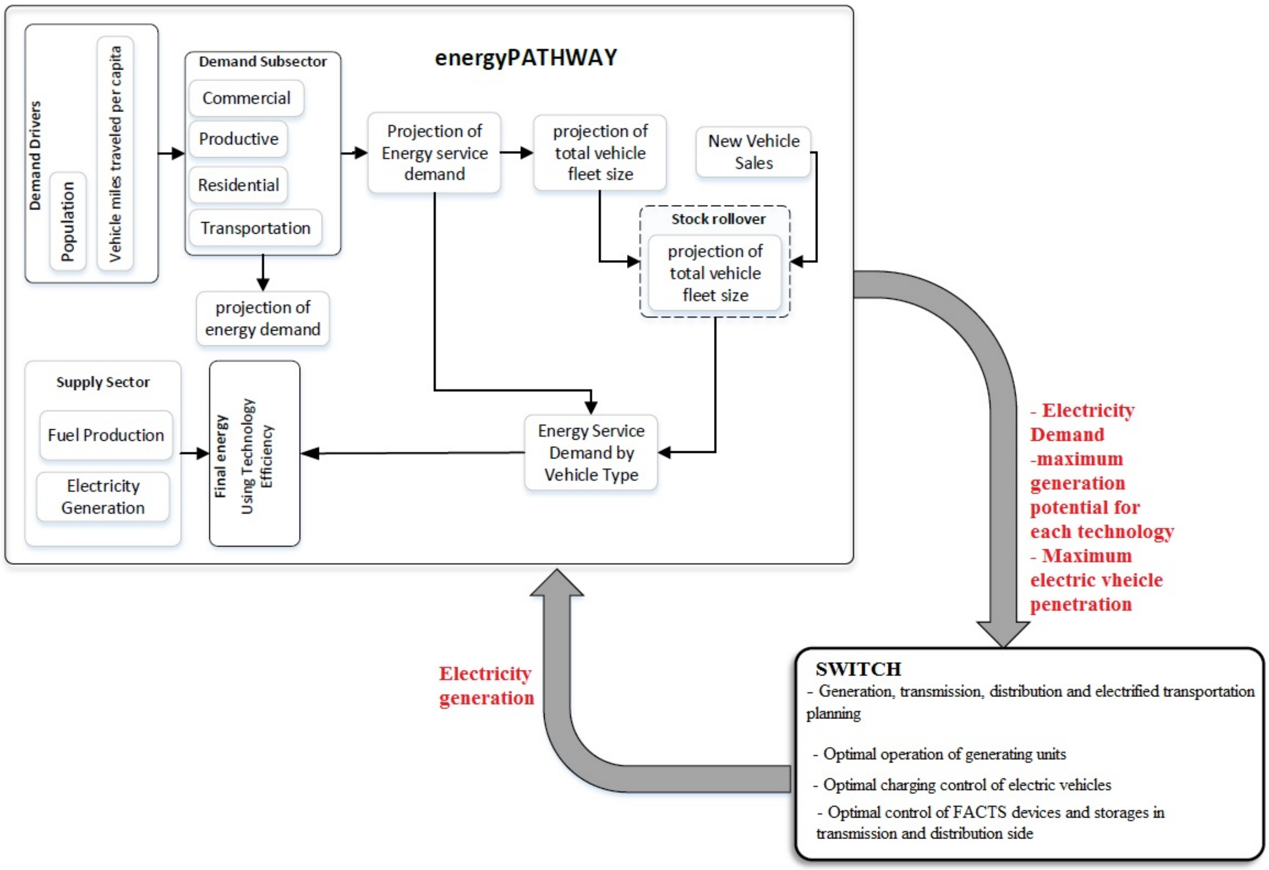

Figure 5: The data that is shared between two models

To invoke the two models in the project, the following modelling process should be used:

- Basic data concerning key demand drivers were supplied by energyPATHWAYS. This included total electricity demand, population projections and service demands (such as passenger kilometers in the transportation sector, number and type of dwellings for the residential sector, etc.) for all sectors. These data are the same for all scenarios, and only had to be passed on once

- Optimization with scenario specific constraint sets was carried out with the SWITCH model, with derivation of major decision variables (for example, additional generating capacity for each class of facilities in each jurisdiction in each time period), along with associated system responses.

- For each scenario a more detailed simulation of system responses was carried out with energyPATHWAYS on year by year basis, with scenario specific input of major decision variables produced by SWITCH.

- Results from the two models were compared to ensure that results were consistent and credible. This has required additional runs with both models to ensure that the models are producing sensibly accurate and consistent results.

First both models are set to the same final demand for energy services through part one of the data bridge. After deriving scenario specific optimum results on how to provide those services in step 2, the results are passed back to energyPATHWAYS via part two of the data bridge. The energyPATHWAYS model was then run with its detailed energy system representation for a credibility check and model result comparison.

# References

[1] IPCC Climate Change et al. Mitigation of climate change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1454, 2014.

[2] Jeffrey Sachs, Emmanuel Guerin, Carl Mas, Guido Schmidt-Traub, Laurence Tubiana, Henri Waisman, Michel Colombier, Claire Bulger, Elana Sulakshana, Kathy Zhang, et al. pathways to deep decarbonization-2014 report. 2014.

[3] EnergyPATHWAY team. Model documentation and methodology. *https://energypathways.github.io/*, pages 1–28, 2016.

[4] Ana Mileva, Josiah Johnston, James H Nelson, and Daniel M Kammen. Power system balancing for deep decarbonization of the electricity sector. *Applied Energy*, 162:1001–1009, 2016.