Deep Decarbonization of Energy Systems: Insights using capacity expansion model

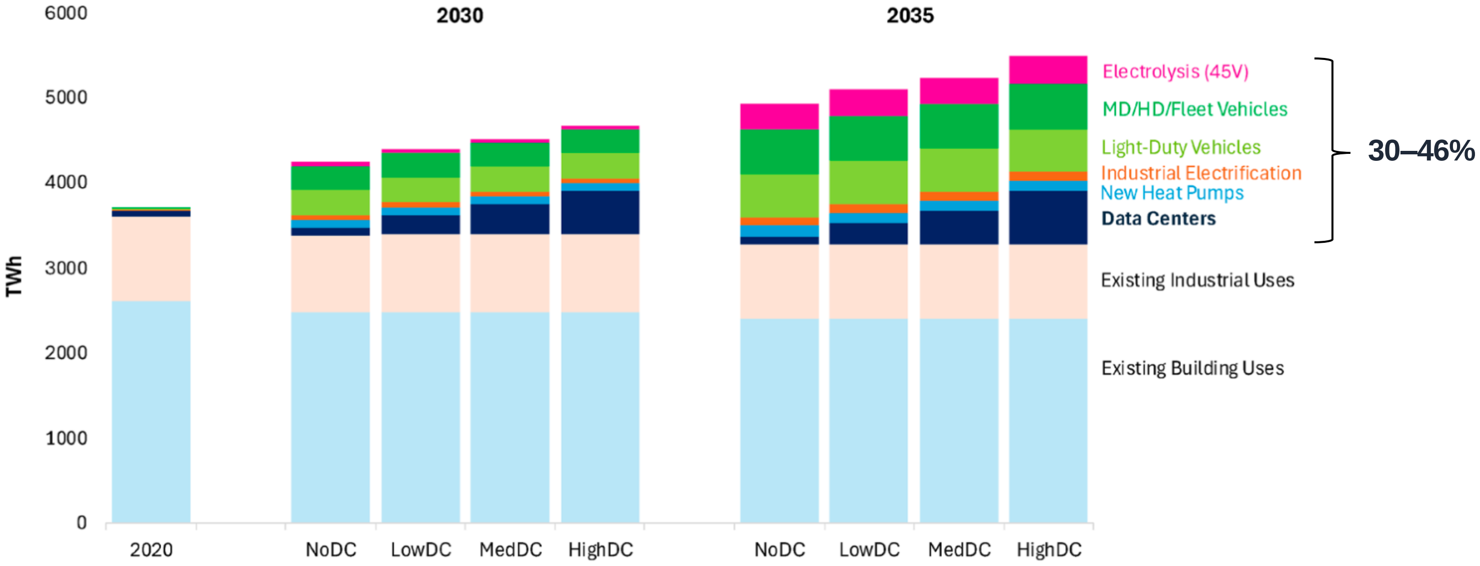
Yifu Ding, Postdoc @ MIT Energy Initiative

yifuding@mit.edu

Why capacity expansion model?

A capacity expansion model determines the optimal investment strategy for expanding energy infrastructure, such as power generation, transmission, and even flexible loads over a planning horizon.

Emerging Electrical Loads and Renewable Generations in Power Grids



The Projected Growth of New Electrical Loads in 2030 and 2035 [1]

[1] EPRI, Powering Data Centers: U.S. Energy System and Emissions Impacts of Growing Loads, Oct 2024

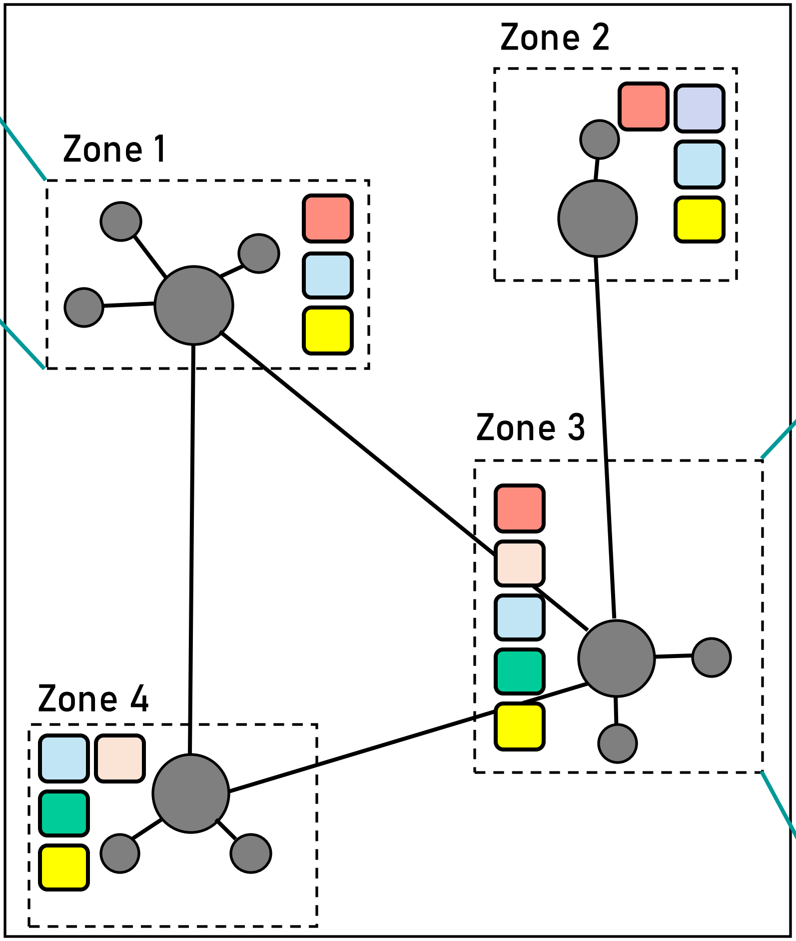
GenX Model

MIT Energy Initiative tool for long-term policy and techno-economic analysis

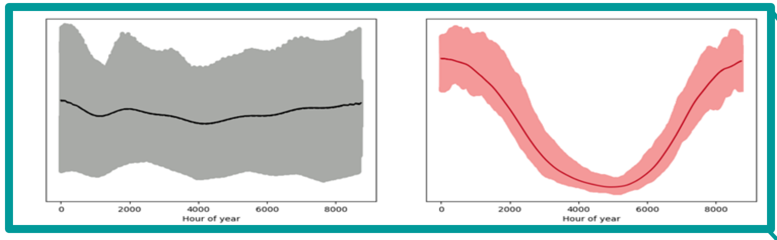
GenX in a nutshell

Inputs

1. The user defines a transmission network (and local distribution)



2. Each zone is defined by an annual electricity (& other) demand timeseries



3. Generation, storage and transmission technologies are defined based on economic, performance, & availability parameters

10MW Wind

Costs:
- Fixed
- Variable
- Startup

Performance:
- Min power
- Availability
- Ramp rate

Li-ion

4MWh / 10MWe

Costs:
- Fixed
- Variable

Performance:
- Capacity
- Cycle eff.
- Self-discharge

1GW Fission

50MW NGCC

200MW NGCC

0.5MW PV

Transmission

4. Public policies and resource constraints are added per-zone or system-wide

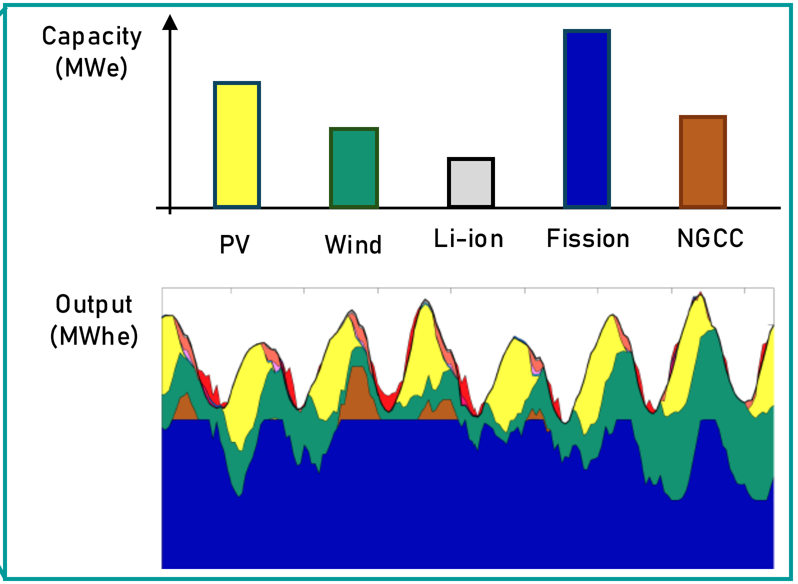
- Capacity reserves
- CO_2 Cap
- CO_2 price
- RPS
- Non-service penalties
- …

Outputs

5. GenX finds the cheapest combination of technologies which meets the demand

Reports system and zone outcomes:
- Costs
- Average price
- Emissions
- Transmission losses
- …

6. GenX returns optimal investment and operation decisions for each zone and line



How do capacity expansion models work?

- Where And How To Invest In Capacity,
- How To Dispatch Or Operate That Capacity,
- Which Consumer Demand Segments To Serve Or Curtail,
- How To Cycle And Commit Thermal Units Subject To Unit Commitment Decisions,
- And Where And How To Invest In Additional Transmission Network Capacity To Increase Power Transfer Capacity Between Zones.

Objective:

Minimize based on planning horizon T and zones Z

- Capital costs of generation capacity
- Fixed and variable operation & maintenance costs
- Value of lost loads
- Fuel Cost, start-up or shut-down costs
- Network expansion costs

How do capacity expansion models work?

CEMs form a constrained optimization problem:

Group all your decision variables into a vector *x*

Minimize the cost of the system: *f(x)*

subject to a set of equality constraints: *g(x) = a*

and a set of inequality constraints: *h(x) <= b*

$\min 10x + 15y$	Objective function (cost)
s.t.	
$x + y \geq 10$	Grid Demand
$55x + 70y \leq 1000$	Construction constraint
$40x + 5y \leq 200$	Emissions constraint
$x, y \geq 0$	Non-negativity constraints

Many CEMs stick to linear constraints

This means the constraints become a matrix: *Ax <= c*

This makes the problem easier to solve so allows for much larger models

How do capacity expansion models work?

Let's say we're modelling a systems with 2 zones, 3 possible resources and 10 time steps

x has at least 66 elements: 6 investment variables and 6x10 power-output variables

The objective function, *f(x)*, is the sum of their operating costs:

$$f(x) = \sum_{i=1:6}\left(\left(\$_{inv} + \$_{fix\ O\&M}\right)_i C_i + \sum_{t=1:10}\left(\$_{fuel} + \$_{var\ O\&M}\right)_i Power_{i,t} + \cdots\right)$$

The constraints look like:

Capacity constraints: $Power_{1,1} \leq C_1$, $Power_{1,2} \leq C_1$, …

Power flow constraints: $\sum_{i\ in\ zone\ 1} Power_{i,1} - Demand_1 - (net\ transmission\ out)_1 = 0$

Storage: $(Stored\ energy)_{i,2} = (Stored\ energy)_{i,1} - (losses)_{i,1} + (net\ charging)_{i,1}$

Emissions: $\sum_{i=1:6}\sum_{t=1:10} Power_{i,t}(Emissions\ intensity)_i \leq (emission\ limit)$

Functions in GenX

! genx_settings.yml U ×

Tutorials > example_systems > 1_three_zones > settings > ! genx_settings.yml

```yaml
OverwriteResults: 0 # Overwrite existing results in output folder or create a new one; 0 = create new folder; 1 = overwrite existing
PrintModel: 0 # Write the model formulation as an output; 0 = active; 1 = not active
NetworkExpansion: 1 # Transmission network expansionl; 0 = not active; 1 = active systemwide
Trans_Loss_Segments: 1 # Number of segments used in piecewise linear approximation of transmission losses; 1 = linear, >2 = piecewis
EnergyShareRequirement: 0 # Minimum qualifying renewables penetration; 0 = not active; 1 = active systemwide
CapacityReserveMargin: 0 # Number of capacity reserve margin constraints; 0 = not active; 1 = active systemwide
CO2Cap: 2 # CO2 emissions cap; 0 = not active (no CO2 emission limit); 1 = mass-based emission limit constraint; 2 = demand + rate-b
StorageLosses: 1 # Energy Share Requirement and CO2 constraints account for energy lost; 0 = not active (DO NOT account for energy l
MinCapReq: 1  # Activate minimum technology carveout constraints; 0 = not active; 1 = active
MaxCapReq: 0  # Activate maximum technology carveout constraints; 0 = not active; 1 = active
ParameterScale: 1 # Turn on parameter scaling wherein demand, capacity and power variables are defined in GW rather than MW. 0 = not
WriteShadowPrices: 1 # Write shadow prices of LP or relaxed MILP; 0 = not active; 1 = active
UCommit: 2 # Unit committment of thermal power plants; 0 = not active; 1 = active using integer clestering; 2 = active using lineari
TimeDomainReduction: 1 # Time domain reduce (i.e. cluster) inputs based on Demand_data.csv, Generators_variability.csv, and Fuels_da
ModelingToGenerateAlternatives: 0 # Modeling to generate alternatives; 0 = not active; 1 = active. Note: produces a single solution
ModelingtoGenerateAlternativeSlack: 0.1 # Slack value as a fraction of least-cost objective in budget constraint used for evaluating
ModelingToGenerateAlternativeIterations: 3 # Number of MGA iterations with maximization and minimization objective
MultiStage: 0 # Multi-stage modeling; 0 if single-stage; 1 if multi-stage.
MethodofMorris: 0 #Flag for turning on the Method of Morris analysis

```

Model Constraints for thermal units- Linear Programming vs. Unit Commitment

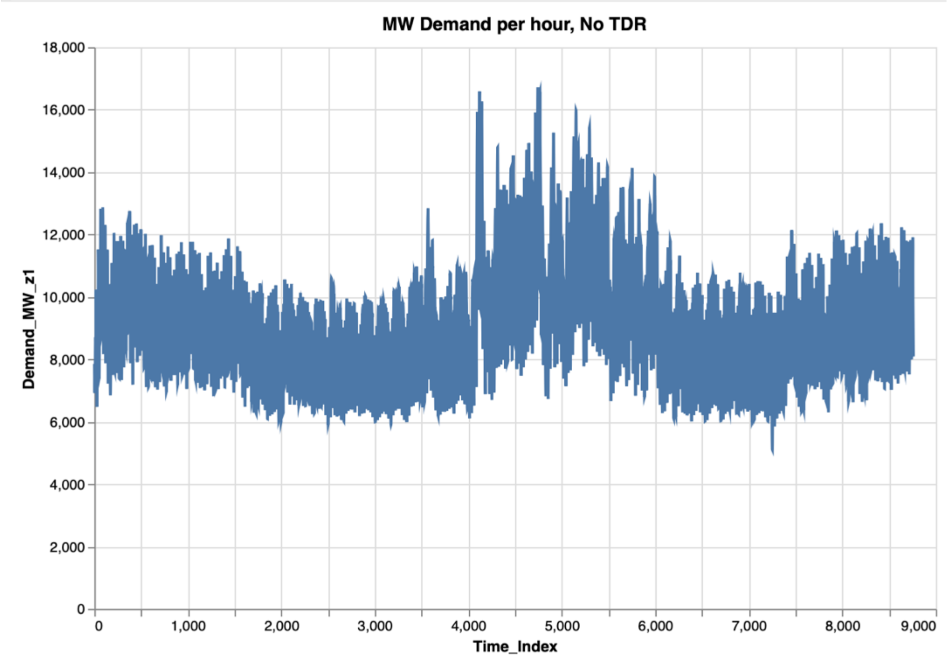
- Many existing models establish each plant's unit commitment and operational constraints (start-up, shut-down, dispatch output, etc.).
- <u>Clustering approach</u>: The same type of power plants are grouped into clusters, standardizing their technical characteristics.
- <u>Linear relaxation</u>: The same type of power plants are grouped into clusters, standardizing their technical characteristics.

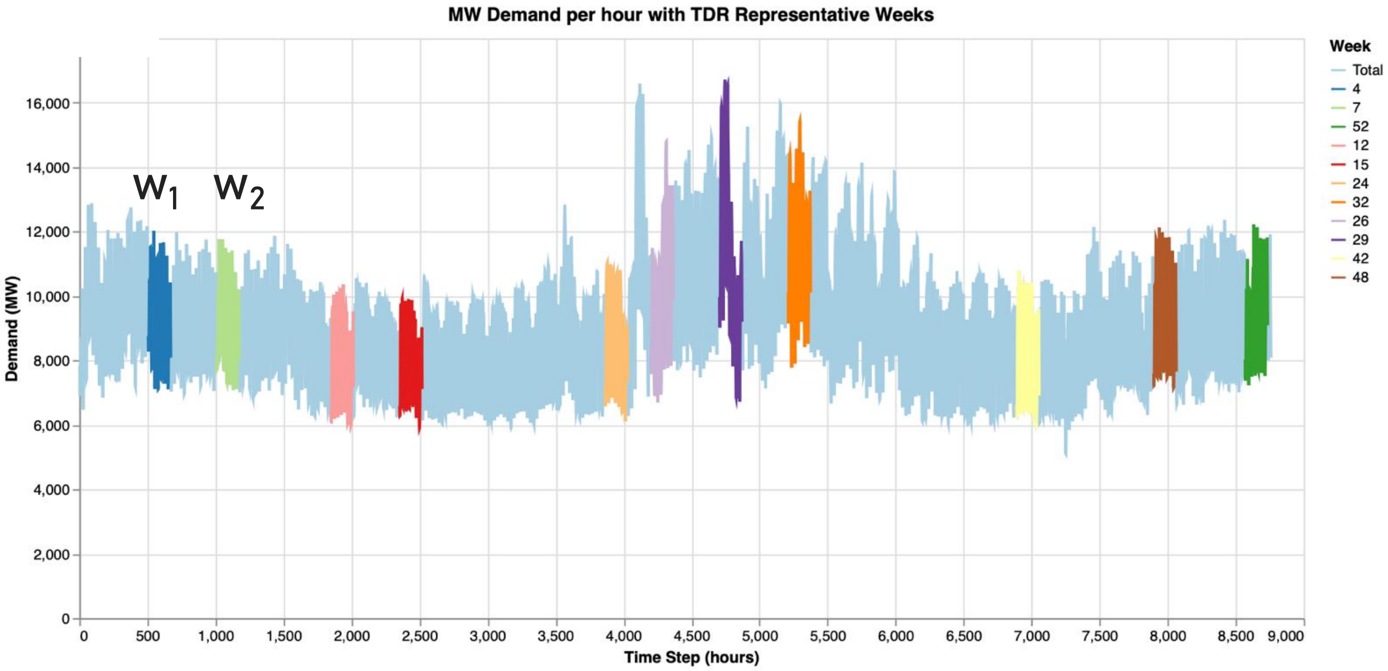
➢ Large set of binary and linear constraints, increased computation time.

➢ Binary decision variables (e.g., plant operation/ plant shut-down) are replaced with positive integer variables.

➢ Positive integer variables are relaxed to linear variables.

Clustering for representative weeks - An effective way to reduce computation costs





An example is clustering annual demand profiles into five representative weeks. Each representative week is assigned to a weight, w_n

Network flow –
Pipeline versus Optimal Power Flow

- Bubbles and Pipes

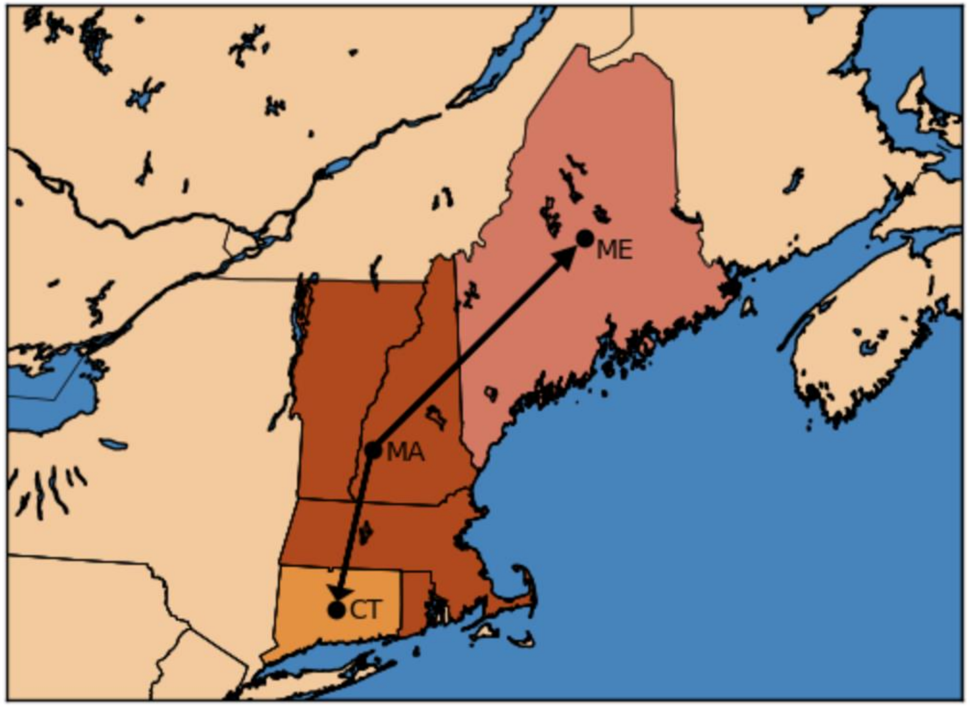
Power flow is only constrained by the line (or corridor) capacity.

- Optimal Power Flow

Power flow is set as a relationship between its voltage, resistance, and the phase angle difference. Phase angle differences are constrained by the maximum angle.

One zone must be set as a reference – slack bus.

Given each line $l \in L$, the time interval $t \in T$

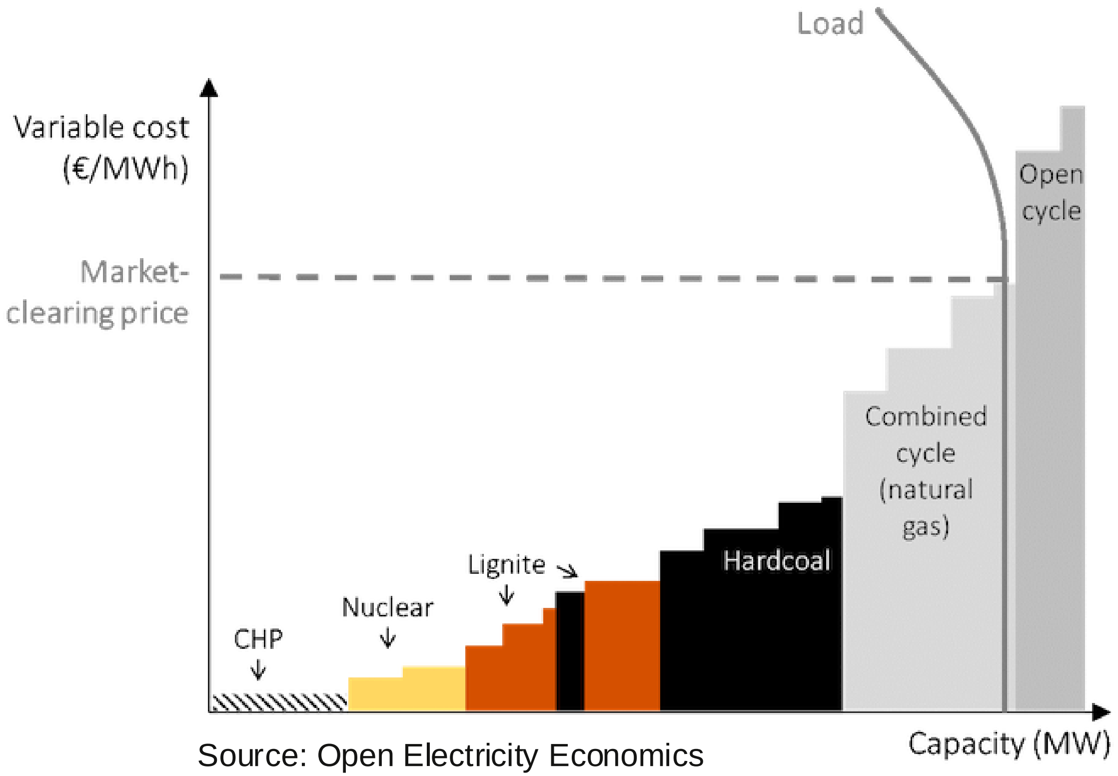


Power and carbon prices

- If the optimal solution exists for linear programming, the dual variable of binding constraints represents the shadow prices.

- Shadow prices give us directly the marginal worth of an additional unit of any of the resources, such as power or carbon prices.

- For example, the dual variable of the power balance can be interpreted as the marginal power price.

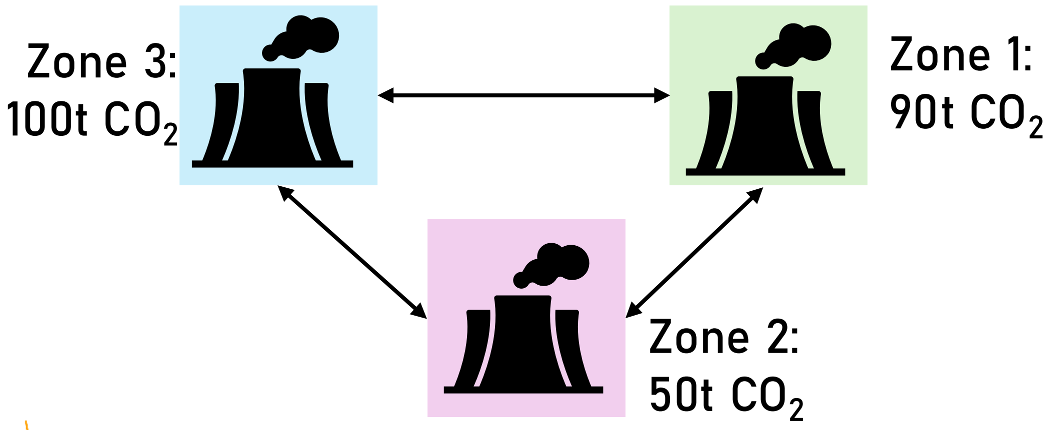


Source: Open Electricity Economics

Carbon policy and energy share requirements

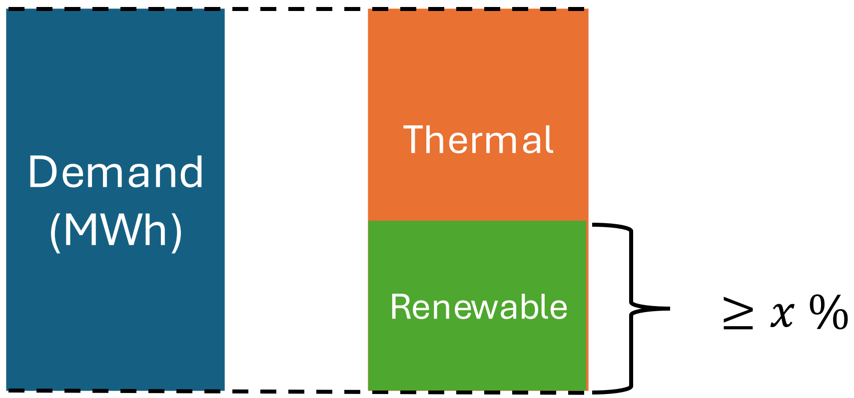
- Carbon cap-and-trading:

The constraint regulates emission limits for one or more model zones, and zones can trade CO2 emissions permits and earn revenue based on their CO2 allowance.



- Energy Share Requirement:

This requires that the annual or hourly MWh generation from a subset of qualifying renewable or low-carbon generators has to be higher than a pre-specified percentage of load from qualifying zones.



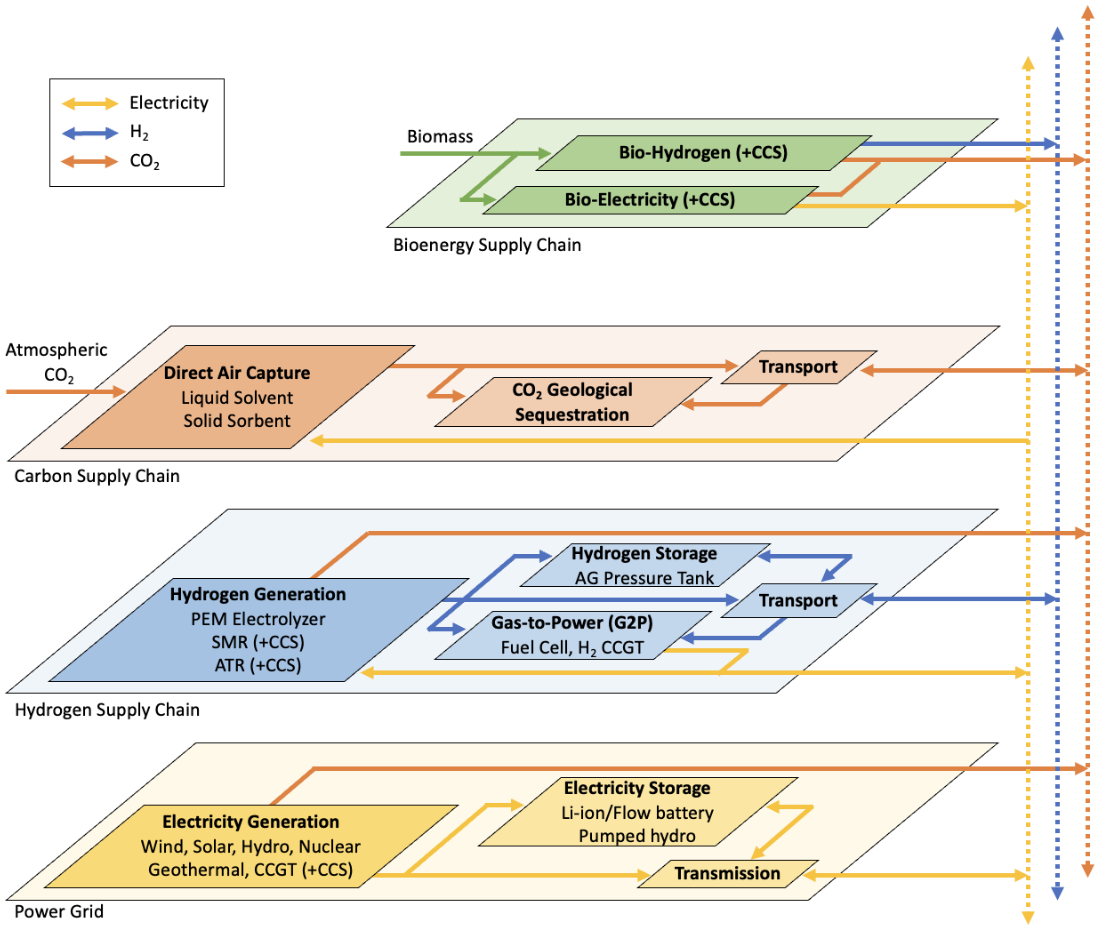
It can be expanded to multiple sectors - DOLPHYN

GenX can currently co-optimize grids with:

- Electricity
- Hydrogen
- Biofuels
- Carbon emissions
- Heat*

Other capacity expansion models:

- PyPSA
- Switch Power System Planning Model
- PowerGenome



MITei

Let's give it a try!

GenX currently uses a command -line interface, CSV file inputs and outputs, and YAML files for settings and configuration.

Inputs

Name
..
policies
resources
settings
system
README.md
Run.jl

Name
..
Demand_data.csv
Fuels_data.csv
Generators_variability.csv
Network.csv

CLI

```
Running HiGHS 1.6.0: Copyright (c) 2023 HiGHS under MIT licence terms
Presolving model
118138 rows, 81183 cols, 467127 nonzeros
110719 rows, 73764 cols, 468669 nonzeros
Presolve : Reductions: rows 110719(-42679); columns 73764(-46375); elements 468669(-46801)
Solving the presolved LP
IPX model has 110719 rows, 73764 columns and 468669 nonzeros
Input
    Number of variables:                                73764
    Number of free variables:                           3696
    Number of constraints:                              110719
    Number of equality constraints:                     16605
    Number of matrix entries:                           468669
    Matrix range:                                       [4e-07, 1e+01]
    RHS range:                                          [8e-01, 4e+03]
    Objective range:                                    [1e-04, 5e+02]
    Bounds range:                                       [2e-03, 1e+01]
Preprocessing
    Dualized model:                                     no
    Number of dense columns:                            15
    Range of scaling factors:                           [5.00e-01, 8.00e+00]
```

Outputs

- capacity.csv
- capacityfactor.csv
- charge.csv
- ChargingCost.csv
- commit.csv
- costs.csv
- curtail.csv
- emissions.csv
- EnergyRevenue.csv
- NetRevenue.csv
- nse.csv
- power.csv
- power_balance.csv
- prices.csv
- RegSubsidyRevenue.csv
- reliability.csv
- shutdown.csv
- start.csv
- status.csv
- storage.csv
- storagebal_duals.csv
- SubsidyRevenue.csv
- time_weights.csv