PREP-SHOT Documentation

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CHAPTER

ONE

OVERVIEW

PREP-SHOT (**P**athways for **R**enewable **E**nergy **P**lanning coupling **S**hort-term **H**ydropower **O**pera**T**ion) is a transparent, modular, and open-source energy expansion model hosted on GitHub. Offering advanced solutions for multi-scale, intertemporal, and cost-effective expansion of energy systems and transmission lines. PREP-SHOT was orginally developed to study the nexus between water and energy systems. The development started in 2021, and in 2022, it was released as an open-source model.

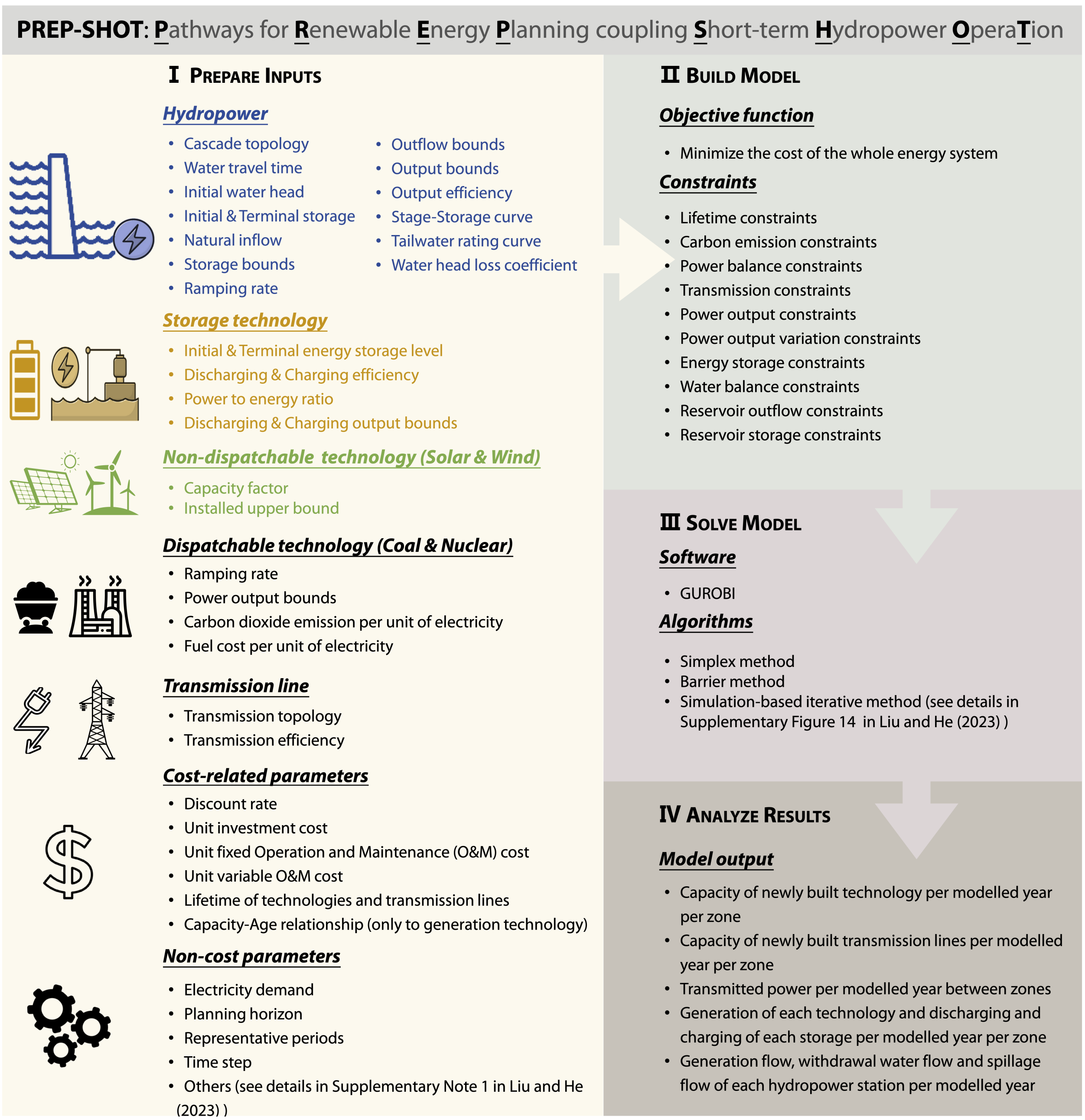
The model sets itself apart from existing energy expansion models through its deeper consideration of hydropower processes. While models such as urbs might treat hydropower as fixed processes, and others like GenX and PLEXOS may not fully capture the dynamic nature of water heads or consolidate multiple hydropower stations into a single unit, PREP-SHOT is uniquely designed to address these oversights.

Our model explicitly considers the plant-level water head dynamics (i.e., time-varying water head and storage) and the system-level network topology of all hydropower stations within a regional grid. This results in a more accurate reflection of the multi-scale dynamic feedbacks between hydropower operation and energy system expansion. Furthermore, it enables the realistic simulation of the magnitude and spatial-temporal variability of hydropower output, particularly in regions with a large number of cascade hydropower stations.

With PREP-SHOT, we aim to answer key questions related to the future of energy planning and utilization:

- How can we effectively plan an energy portfolio and new transmission capacity under deep uncertainty?
- How can we quantify the impacts of variable hydropower on the generation and capacity of future energy portfolios?

HOW IT WORKS


PREP-SHOT: Pathways for Renewable Energy Planning coupling Short-term Hydropower OperaTion
I PREPARE INPUTS
Hydropower
Cascade topology
Water travel time
Initial water head
Initial & Terminal storage
Natural inflow
Storage bounds
Ramping rate
Outflow bounds
Output bounds
Output efficiency
Stage-Storage curve
Tailwater rating curve
Water head loss coefficient
Storage technology
Initial & Terminal energy storage level
Discharging & Charging efficiency
Power to energy ratio
Discharging & Charging output bounds
Non-dispatchable technology (Solar & Wind)
Capacity factor
Installed upper bound
Dispatchable technology (Coal & Nuclear)
Ramping rate
Power output bounds
Carbon dioxide emission per unit of electricity
Fuel cost per unit of electricity
Transmission line
Transmission topology
Transmission efficiency
Cost-related parameters
Discount rate
Unit investment cost
Unit fixed Operation and Maintenance (O&M) cost
Unit variable O&M cost
Lifetime of technologies and transmission lines
Capacity-Age relationship (only to generation technology)
Non-cost parameters
Electricity demand
Planning horizon
Representative periods
Time step
Others (see details in Supplementary Note 1 in Liu and He (2023))
II BUILD MODEL
Objective function
Minimize the cost of the whole energy system
Constraints
Lifetime constraints
Carbon emission constraints
Power balance constraints
Transmission constraints
Power output constraints
Power output variation constraints
Energy storage constraints
Water balance constraints
Reservoir outflow constraints
Reservoir storage constraints
III SOLVE MODEL
Software
GUROBI
Algorithms
Simplex method
Barrier method
Simulation-based iterative method (see details in Supplementary Figure 14 in Liu and He (2023))
IV ANALYZE RESULTS
Model output
Capacity of newly built technology per modelled year per zone
Capacity of newly built transmission lines per modelled year per zone
Transmitted power per modelled year between zones
Generation of each technology and discharging and charging of each storage per modelled year per zone
Generation flow, withdrawal water flow and spillage flow of each hydropower station per modelled year

Source: Liu and He (2023).

CHAPTER

THREE

KEY FEATURES

- PREP-SHOT is an optimization model based on linear programming for energy systems with multiple zones.
- It aims to minimize costs while meeting the given demand time series.
- By default, it operates on hourly-spaced time steps, but this can be adjusted.
- The input data is in Excel format, while output data is generated in a NetCDF format using `Xarray`.
- It supports multiple types of solvers such as Gurobi, CPLEX, MOSEK, and GLPK via Pyomo.
- It allows input of multiple scenarios for specific parameters.
- As a pure Python program, it benefits from the use of `pandas` and `Xarray`, simplifying complex data analysis and promoting extensibility.

CHAPTER

FOUR

OFFLINE DOCUMENTATION

To browse the documentation offline, you can download an PDF copy for offline reading (Synchronize updates with online documentation).

4.1 Installation

This page provides instructions on how to install and use PREP-SHOT. The installation process is divided into the following steps:

4.1.1 Step 1: Install Gurobi

Gurobi is an optimization solver known for its speed and efficiency. You can obtain a free academic license by following Gurobi Instructions.

4.1.2 Step 2: Install Miniconda

Miniconda is a package management tool that helps manage the Python packages required for PREP-SHOT. You can install it by following the official instructions.

To verify that Miniconda has been installed successfully, you can run the `conda -V` command to check its version.

4.1.3 Step 3: Download PREP-SHOT

Ensure you have downloaded the PREP-SHOT model from the GitHub repository.

You may either clone the repository using the command:

```
git clone https://github.com/PREP-NexT/PREP-SHOT.git
```

or download the repository as a zip file here.

4.1.4 Step 4: Create the Conda Environment

The `prep-shot.yml` file contains all the dependencies for the project. You can use it to create a new environment for PREP-SHOT. This environment isolates the project and its dependencies from other Python projects to prevent package conflicts.

```
conda env create -f prep-shot.yml
conda activate prep-shot
```

4.1.5 Step 5: Run the Model

Once the environment is activated, you can run an example with the following command:

```
python run.py
```

4.2 Model Inputs/Outputs

The model requires several input parameters, provided via input files. These parameters, their dimensions, and descriptions are as follows:

4.2.1 Inputs

The parameters used, their desciptions, and their input file name in the model are as follows:

Table 1: Parameters

Parameter [Unit]	Description	Input file[Page 12, 1]
historical capacity[2] [MW]	The capacity of each technology in each zone for each year, taking into account the number of years that each technology has been in operation starting from the beginning of the planning period.	historical_capacity
capacity factor [N/A]	Capacity factor of different non-dispatchable technologies.	capacity_factor
carbon emission limit [tCO2]	Carbon emission limit of different zones.	carbon_emission_limit
emission factor [tCO2/MWh]	Emission factor of different technologies.	carbon_content
water delay time [N/A]	Water delay time of connection between reservoirs.	water_delay_time
demand [MW]	Demand of different balancing authorities.	demand
discount factor [N/A]	Discount factor for each year.	discount_factor
distance [km]	Distance of different pair of zones.	distance
discharge efficiency [N/A]	Discharge efficiency of storage technologies.	discharge_ efficiency
charge efficiency [N/A]	Charge efficiency of storage technologies.	charge_ efficiency
power to energy ratio [MW/MWh]	Power to energy ratio ratio of storage technologies.	power_to_ energy_ratio

continues on next page

Table 1 – continued from previous page

Parameter [Unit]	Description	Input file[Page 12, 1]
fuel price [dollar/MWh]	Fuel price of different technologies.	fuel_price
hydropower[3] [MW]	Predefined hydropower output of all reservoirs.	hydropower
inflow [m3/s]	Inflow of all reservoirs.	inflow
initial energy storage level [1/MWh]	Initial energy storage level of different storage technologies.	initial_energy_storage_level
lifetime [yr]	Lifetime of different technologies.	lifetime
new technology lower bound [MW]	Lower bound of newly-built installed capacity of different technologies for each investment year.	new_technology_lower_bound
new technology upper bound [MW]	Upper bound of newly-built installed capacity of different technologies for each investment year.	new_technology_upper_bound
ramp down [1/MW]	Ramp down rate of different technologies.	ramp_down
ramp up [1/MW]	Ramp up rate of different technologies.	ramp_up
reservoir characteristics [As per data sheet]	Reservoir characteristics data includes designed water head, maximum storage, minimum storage, operational efficiency, area of affiliation, installed capacity, maximum power output, minimum power output, maximum outflow, minimum outflow, and maximum generation outflow.	reservoir_characteristics
reservoir storage lower bound [m3]	Lower bound of volume of hydropower reservoirs.	reservoir_storage_lower_bound
final reservoir storage level [m3]	Final volume of hydropower reservoirs.	final_reservoir_storage_level
initial reservoir storage level [m3]	Initial volume of hydropower reservoirs.	initial_reservoir_storage_level
reservoir storage upper bound [m3]	Upper bound of volume of hydropower reservoirs.	reservoir_storage_upper_bound
Investmented OM cost [dollar/MW/yr]	Fixed operation and maintenance cost of different technologies.	technology_fixed_OM_cost
technology investment cost [dollar/MW]	Investment cost of different technologies.	technology_investment_cost
technology portfolio [MW]	Existing total installed capacity across all zones.	technology_portfolio
technology upper bound[4] [MW]	Upper bound of installed capacity of different technologies.	technology_upper_bound
technology variable OM cost [dollar/MWh]	Variable operation and maintenance costs of different technologies.	technology_variable_OM_cost
transmission line investment cost [dollar/MW/km]	Investment cost of transmission lines (if there is no exising nor planned transmission lines between two specific zones, leave the data entries blank).	transmission_line_investment_cost
transmission line efficiency [N/A]	Efficiency of transmission lines across all zones.	transmission_line_efficiency
transmission line fixed OM cost [dollar/MW]	Fixed operation and maintenance costs of transmission lines.	transmission_line_fixed_OM_cost

continues on next page

Table 1 – continued from previous page

Parameter [Unit]	Description	Input file[Page 12, 1]
transmission line variable OM cost [dollar/MWh]	Variable operations and maintenance costs of transmission lines.	transmission_line _variable_cost
transmission line lifetime [yr]	Lifetime of transmission lines.	transmission_line_ lifetime
technology type [N/A]	Categories of different technologies.	technology_type
reservoir tailrace level-discharge function [m & m3/s]	Relationship between tailrace level and total discharge for different reservoirs.	reservoir_tailrace_ level_discharge_ function
reservoir forebay level-volume function [m & m3]	Relationship between forebay level and volume for different reservoirs	reservoir_forebay_ level_volume_ function

Note:

- *inf* refers to Infinity, indicating that there is no upper bound.
- *None* refers to a null value for current item.

4.2.2 Outputs

The output of the model is stored in a NetCDF file, please refer to this simple tutorial and official documentation of Xarray to understand how to manipulate NetCDF files.

The output file contains the following variables:

[1] The input files format is `.xlsx`.

[2] For instance, assuming the planning period spans from 2020 to 2050, with 2020 being the starting point, let's consider a technology that has been in operation since 2019. In this case, 2020 would mark its 2nd year of operation within the planning period. These inputs are useful for modelling the retirement of existing technologies.

[3] To model the simplified hydropower operation.

[4] To model the potential of technologies with land, fuel, and water constraints.

Table 2: Output Variables

Variable name [Unit]	Description
trans_import_v [MW]	The electrical power transmitted from Zone 1 and effectively received by Zone 2 through the transmission line, after adjusting for transmission losses.
trans_export_v [MW]	The electrical power initially sent out by Zone 1 for transmission to Zone 2 via the transmission line, before adjusting for any transmission and distribution losses during its journey to Zone 2.
gen_v [MW]	Generated electricity from different technologies.
install_v [MW]	Existing installed capacity of different technologies.
carbon_v [Ton]	Carbon emissions across different years.
charge_v [MW]	Charged electricity of different storage technologies.
cost_v [dollar]	Total cost over the planning period.
cost_var_v [dollar]	Variable cost over the planning period.
cost_fix_v [dollar]	Fixed cost over the planning period.
cost_new_v [dollar]	Investment cost of technologies over the planning period.
cost_newline_v [dollar]	Investment cost of transmission lines over the planning period.
income_v [dollar]	Saved cost due to abstracted water resources over the planning period.
genflow_v [m3/s]	Generated water flow of different reservoirs.
spillflow_v [m3/s]	Spilled water flow of different reservoirs.

4.2.3 Execute various scenarios

By employing command-line parameters, you can execute different scenarios using the model. For example, if you wish to run a scenario referred to as "low demand," you can prepare input data named `demand_low.xlsx`. Subsequently, when running the model, you can utilize command-line parameters to specify the scenario value. For instance, you can execute the model by executing the command `python run.py --demand=low`.

4.2.4 Tuning Model Parameters

This section will guide you on how to tune the PREP-SHOT model parameters to compute the energy system for your needs. After you have prepared your input data based on the previous sections, you can proceed to tune the model parameters before you run it.

Within the root directory of the model, you will find a JSON file containing the parameters that you can tune for the model, named `config.json`. This file contains the following parameters:

Model Parameter	Description
input_folder	Specifies the name of the folder containing the input data.
output_filename	Specifies the name of the output file.
hour	Specifies the number of hours in each time period.
month	Specifies the number of months in each time period.
dt	Specifies the timestep for the simulation in hours.
hours_in_year	Specifies the number of hours in a year. Typically, this is set to 8760.
ishydro	Specifies whether to include hydropower in the optimization problem.
error_threshold	Specifies the error threshold for the model, while iterating for a solution. This parameter controls the convergence of the hydro model.
iteration_number	Specifies the maximum number of iterations for the hydro model, while iterating for a solution.
solver	Specifies the solver to be used for the optimization problem.
timelimit	Specifies the maximum time limit for the solver to solve the optimization problem in seconds.

After you have tuned the parameters, you can run the model by following the steps in the *Installation* page.

You can also try out the model with the sample data provided in the `input` folder. Refer to the *Model Inputs/Outputs* page for a walkthrough of this example, inspried by real-world data.

4.3 Running cases

In this tutorial, we'll guide you through running your first PREP-SHOT model! This example will illustrate an electricity capacity expansion scenario.

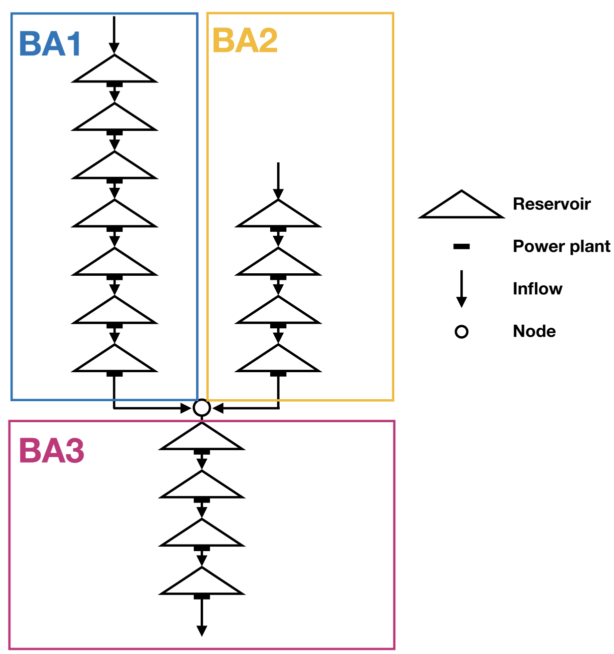
4.3.1 Scenario Background

This scenario is inspired by real-world data, drawing primarily from the following resources:

- U.S. Energy Information Administration (EIA)
- U.S. Army Corps of Engineers (USACE)
- U.S. National Renewable Energy Laboratory (NREL)

In this tutorial, we examine a cascading hydropower system, consisting of a network of 15 interconnected hydropower stations. We shall assume the presence of three balancing authorities (BAs) - BA1, BA2, and BA3. Each of these authorities will have distinct jurisdictional connections with their local reservoirs.

The jurisdictional connections of the stations, reservoirs, and balancing authorities are illustrated below:



For this tutorial, we assume that, apart from hydropower, no other existing power generation technologies or transmission lines are in place.

However, we will be exploring the potential of incorporating four additional technologies into our grid:

- Coal-fired plants
- Wind power plants

- Solar power plants
- Energy storage plants

The objective of our scenario is to devise an electric mix pathway from 2020 to 2030 that enables the achievement of zero-carbon emissions. We shall use a 48-hour period as a representative sample for our analysis.

4.4 Mathematical Notations

This page provides a detailed description of the mathematical notations used for formulating the model's objective function and constraints (Liu and He, 2023).

4.4.1 Unit List

The description of the units used in this page are as follows:

Unit	Description
hr	Hour
yr	Year
dollar	US Dollar
kW	Kilowatt
MW	Megawatt
MWh	Megawatt-hour
MWy	Megawatt-year
MW-km	Megawatt-kilometer
tonne	Tonne
m	Meter
s	Second
N/A	Not Applicable

4.4.2 Set List

Set	Description	Unit
$e \in \mathcal{E}$	Technology	N/A
$h, h_{\text{start}}, h_{\text{end}} \in \mathcal{H}$	Hour	hr
$y, y_{\text{next}}, y_{\text{pre}}, y_{\text{start}}, y_{\text{end}} \in \mathcal{Y}$	Year	yr
$m \in \mathcal{M}$	Month	N/A
$z, z_{\text{from}}, z_{\text{to}} \in \mathcal{Z}$	Zone	N/A
$\text{age} \in \mathcal{AGE}$	Operation time	yr
$s, \text{su} \in \mathcal{S}$	Hydropower station	N/A
$\mathcal{IU}_s \in \mathcal{S}$	Immediate upstream hydropower stations of hydropower station s	N/A
$\mathcal{SZ}_z \in \mathcal{S}$	Subset of hydropower stations located in zone z	N/A
$\mathcal{DISP} \in \mathcal{E}$	Subset of dispatchable technology	N/A
$\mathcal{NDISP} \in \mathcal{E}$	Subset of non-dispatchable technology	N/A
$\mathcal{STOR} \in \mathcal{E}$	Subset of storage technology	N/A

4.4.3 Variable List

Symbol	Description	Unit
$\text{cost}^{\text{total}}$	System-wide total cost.	dollar
$\text{cost}^{\text{var}}_{\text{tech}}$	System-wide variable Operation and Maintenance (O&M) cost of technologies.	dollar
$\text{cost}^{\text{fuel}}$	System-wide fuel cost of technologies.	dollar
$\text{cost}^{\text{fix}}_{\text{tech}}$	System-wide fixed O&M cost of technologies.	dollar
$\text{cost}^{\text{fix}}_{\text{line}}$	System-wide fixed O&M cost of transmission lines.	dollar
$\text{cost}^{\text{inv}}_{\text{tech}}$	System-wide capital cost of technologies.	dollar
$\text{cost}^{\text{inv}}_{\text{line}}$	System-wide capital cost of transmission lines.	dollar
$\text{cost}^{\text{annualfuel}}_{y}$	Fuel cost of technologies in the modelled year:math:y (the present value of modelled year y).	dollar
$\text{cost}^{\text{fuel}}_{y}$	Fuel cost of technologies accumulated from modelled year y to a non-modelled year before the immediate next modelled year (the present value of modelled year y).	dollar
$\text{gen}_{h,m,y,z,e}$	Power generation of technology e in zone z in hour h in month m of year y.	MWh
$\text{charge}_{h,m,y,z,e}$	Charging electricity of storage technology e in zone z in hour h in month m of year y.	MWh
$\text{export}_{h,m,y,z_{\text{from}},z_{\text{to}}}$	Electric energy exported from zone z_{from} to zone z_{to} in hour h in month m of year y.	MWh
$\text{import}_{h,m,y,z_{\text{from}},z_{\text{to}}}$	Electric energy imported from zone z_{from} to zone z_{to} in hour h in month m of year y.	MWh
$\text{storage}^{\text{energy}}_{h,m,y,z,e}$	Energy storage level of storage technology e in hour h in month m of year y in zone z.	MWh
$\text{storage}^{\text{reservoir}}_{s,h,m,y}$	Reservoir storage corresponding to hydropower station s in hour h in month m of year y.	m^3
$\text{power}_{h,m,y,z,e}$	Overall power output of technology e in zone z in hour h in month m of year y.	MW
$\text{power}^{c}_{h,m,y,z,e}$	Charging power of storage technology e in zone z in hour h in month m of year y.	MW
$\text{power}^{\text{up}}_{h,m,y,z,e}$	Increment in power output of technology e in zone z from hour h-1 to hour h in month m of year y.	MW
$\text{power}^{\text{down}}_{h,m,y,z,e}$	Decrement in power output of technology e in zone z from hour h-1 to hour h in month m of year y.	MW
$\text{power}^{\text{hydro}}_{s,h,m,y}$	Power output of hydropower station s in hour h in month m of year y.	MW
$\text{cap}^{\text{existingtech}}_{y,z,e}$	Existing installed capacity of technology e in year y in zone z.	MW
$\text{cap}^{\text{existingline}}_{y,z_{\text{from}},z_{\text{to}}}$	Existing transmission capacity in year y from zone z_{from} to zone z_{to}.	MW
$\text{cap}^{\text{invtech}}_{y,z,e}$	Installed capacity of newly built technology e in year y in zone z.	MW
$\text{cap}^{\text{invline}}_{y,z_{\text{from}},z_{\text{to}}}$	Capacity of newly built transmission lines from zone z_{from} to zone z_{to} in year y	MW
$\text{cap}^{\text{remaining}}_{y,z,e}$	Remaining installed capacity of technology e in year y in zone z	MW
$\text{carbon}^{\text{tech}}_{y,e}$	Carbon dioxide equivalent emissions of technology e in year y	tonne
carbon_{y}	Carbon dioxide equivalent emissions of the entire energy system in year y	tonne
$\text{inflow}^{\text{total}}_{s,h,m,y}$	Total inflow of reservoir corresponding to hydropower station s in hour h in month m of year y	m^3/s
$\text{outflow}^{\text{total}}_{s,h,m,y}$	Total outflow of reservoir corresponding to hydropower station s in hour h in month m of year y	m^3/s
$\text{outflow}^{\text{gen}}_{s,h,m,y}$	Generation outflow of reservoir corresponding to hydropower station s in hour h in month m of year y	m^3/s
$\text{outflow}^{\text{withdraw}}_{s,h,m,y}$	Water withdrawal of reservoir corresponding to hydropower station s in hour h in month m of year y	m^3/s

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Table 3 – continued from previous page

Symbol	Description	Unit
$\mathrm{outflow}^{\mathrm{spillage}}_{s,h,m,y}$	Spillage outflow of reservoir corresponding to hydropower station s in hour h in month m of year y	m^3/s
$\mathrm{head}^{\mathrm{net}}_{s,h,m,y}$	Net water head of hydropower station s in hour h in month m of year y	m
$\mathrm{head}^{\mathrm{loss}}_{s,h,m,y}$	Water head loss of hydropower station s in hour h in month m of year y	m
$z^{\mathrm{forebay}}_{s,h,m,y}$	Forebay water level of reservoir corresponding to hydropower station s in hour h in month m of year y	m
$z^{\mathrm{tailrace}}_{s,h,m,y}$	Tailrace water level of reservoir corresponding to hydropower station s in hour h in month m of year y	m

4.4.4 Parameter List

Symbol	Description	Unit
$C^{\mathrm{vartech}}_{y,z,e}$	Variable O&M cost per unit power generation from technology e in year y in zone z.	dollar/MWh
$C^{\mathrm{fuel}}_{y,z,e}$	Fuel cost per unit power generation from technology e in year y in zone z.	dollar/MWh
$C^{\mathrm{fixtech}}_{y,z,e}$	Fixed O&M cost per year per unit existing capacity of technology e in year y in zone z.	dollar/MW-yr
$C^{\mathrm{invtech}}_{y,z,e}$	Capital cost per unit installed capacity of technology e in year y in zone z.	dollar/MW
$C^{\mathrm{varline}}_{y,z_{\mathrm{from}},z_{\mathrm{to}}}$	Variable O&M cost per unit transmitted electricity from zone z_{from} to zone z_{to} in year y.	dollar/MWh
$C^{\mathrm{fixline}}_{y,z_{\mathrm{from}},z_{\mathrm{to}}}$	Fixed O&M cost per year per unit existing capacity of transmission line from zone z_{from} to zone z_{to} in year y.	dollar/MW-yr
$C^{\mathrm{invline}}_{y,z_{\mathrm{from}},z_{\mathrm{to}}}$	Capital cost per unit expansion of transmission line from zone z_{from} to zone z_{to} in year y.	dollar/MW
$\mathrm{CARBON}_{y,z,e}$	Carbon dioxide equivalent emission per unit power generation from technology e in year y in zone z.	tonne/MWh
$\overline{\mathrm{CARBON}}_y$	Upper bound of carbon dioxide equivalent emission summed across all zones and technologies in year y.	tonne
$\mathrm{DEMAND}_{h,m,y,z}$	Average power demand in hour h in month m of year y in zone z.	MW
$\mathrm{CAP}^{\mathrm{inittech}}_{\mathrm{age},z,e}$	Initial installed capacity of technology e with the operation time of age years in zone z.	N/A
$\mathrm{CAP}^{\mathrm{initline}}_{\mathrm{age},z_{\mathrm{from}},z_{\mathrm{to}}}$	Initial installed capacity of transmission lines with the operation time of age years from zone z_{from} to zone z_{to}.	MW
$\mathrm{CAP}^{\mathrm{hydro}}_s$	Nameplate capacity of hydropower station s.	MW
$\underline{\mathrm{POWER}}^{\mathrm{hydro}}_s$	Guaranteed minimum power output of hydropower station s.	N/A
$\underline{\mathrm{POWER}}^{c}_{h,m,y,z,e}$	Minimum charge power of storage technology e in hour h in month m of year y in zone z, expressed as a percentage of the existing capacity of storage technology e.	N/A
$\mathrm{STORAGE}^{\mathrm{energy}}_{m,y,z,e}$	Energy storage level of technology e at the beginning of month m of year y in zone z, expressed as a percentage of the maximum energy storage capacity of storage technology e.	N/A
R^{up}_e	Allowed maximum ramping up capacity of technology e in two successive periods, expressed as a percentage of the existing capacity of storage technology e.	1/hr

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Table 4 – continued from previous page

Symbol	Description	Unit
R_e^{down}	Allowed maximum ramping down capacity of technology e in two successive periods, expressed as a percentage of the existing capacity of storage technology e.	1/hr
$\text{STORAGE}_{s,m,y}^{\text{initreservoir}}$	Initial reservoir storage corresponding to hydropower station s in month m of year y.	m^3
$\text{STORAGE}_{s,m,y}^{\text{endreservoir}}$	Terminal reservoir storage corresponding to hydropower station s in month m of year y.	m^3
$\overline{\text{STORAGE}}_{s}^{\text{reservoir}}$	Upper bound of reservoir storage corresponding to hydropower station s.	m^3
$\underline{\text{STORAGE}}_{s}^{\text{reservoir}}$	Lower bound of reservoir storage corresponding to hydropower station s.	m^3
$\text{INFLOW}_{s,h,m,y}^{\text{net}}$	Net inflow of reservoir corresponding to hydropower station s in hour h in month m of year y.	m^3/s
$\text{OUTFLOW}_{s}^{\text{gen}}$	Maximum outflow that can be released through turbines of hydropower station s.	m^3/s
$\text{OUTFLOW}_{s}^{\text{spillage}}$	Maximum outflow that can be released through spillway of reservoir corresponding to hydropower station s.	m^3/s
OUTFLOW_{s}	Minimum outflow of reservoir corresponding to hydropower station s to meet water supply, environmental flow requirements, flood management, and others.	m^3/s
ω	Weight factor to extrapolate representative operation day(s) to a full year (8760 hours).	N/A
ρ	Density of water.	kg/m^3
g	Acceleration of gravity.	m/s^2
$\eta_{y,e}^{\text{in}}$	Charging efficiency of storage technology e in year y.	N/A
$\eta_{y,e}^{\text{out}}$	Generation efficiency of technology e in year y.	N/A
η_s	Generation efficiency of converting water energy to electric energy in hydropower station s.	N/A
$\eta_{z_{\text{from}},z_{\text{to}}}^{\text{trans}}$	Transmission efficiency of transmission lines from zone z_{from} to zone z_{to}.	N/A
$\tau_{\text{su},s}$	Water travel (or propagation) time from the upstream hydropower station su to the immediate downstream hydropower station s.	hr
Δh	Time step.	hr
r	Discount rate.	N/A
T_e	Lifetime of technology e.	yr
T_{line}	Lifetime of transmission line.	yr
EP_e	Power to energy ratio of storage technology e.	hr

4.4.5 Objective Functions

Costs

The objective function of the model is to minimize the net present value of the system's cost. This includes capital cost, fixed O&M cost, variable cost and fuel cost by cost type, technology cost, transmission line cost by the source of cost, and operation cost and planning cost by the source of cost.

The cost equations are defined as follows:

$$\min \overbrace{\text{cost}^{\text{total}}}^{\text{System-wide cost}} = \underbrace{\text{cost}_{\text{tech}}^{\text{var}}}_{\text{Variable O\&M cost of technologies}} + \overbrace{\text{cost}_{\text{line}}^{\text{var}}}^{\text{Variable O\&M cost of transmission lines}} + \overbrace{\text{cost}^{\text{fuel}}}^{\text{Fuel cost}} + \overbrace{\text{cost}_{\text{tech}}^{\text{fix}}}^{\text{Fixed O\&M cost of technologies}} + \underbrace{\text{cost}_{\text{line}}^{\text{fix}}}_{\text{Fixed O\&M cost of transmission lines}} + \underbrace{\text{cost}_{\text{tech}}^{\text{inv}}}_{\text{Investment cost of technologies}} + \overbrace{\text{cost}_{\text{line}}^{\text{inv}}}^{\text{Investment cost of transmission lines}}$$

$$\text{cost}_{\text{tech}}^{\text{var}} = \frac{\sum_{h,m,y,z,\text{e}} C_{y,z,\text{e}}^{\text{tech-var}} \times \text{gen}_{\text{h,m,y,z,e}}}{\omega} \times \text{factor}_{\text{y}}^{\text{var}}$$

$$\text{cost}_{\text{line}}^{\text{var}} = \frac{\sum_{h,m,y,z_s,z_o} C_{y,z}^{\text{line-var}} \times \text{export}_{\text{h,m,y,z}_\text{s}\text{,z}_\text{o}}}{\omega} \times \text{factor}_{\text{y}}^{\text{var}}$$

$$\text{cost}^{\text{fuel}} = \frac{\sum_{h,m,y,z,\text{e}} C_{y,z,\text{e}}^{\text{fuel}} \times \text{gen}_{\text{h,m,y,z,e}}}{\omega} \times \text{factor}_{\text{y}}^{\text{var}}$$

$$\text{cost}_{\text{tech}}^{\text{fix}} = \sum_{y,z,\text{e}} C_{y,z,\text{e}}^{\text{tech-fix}} \times \text{cap}_{\text{y,z,e}}^{\text{existing-tech}} \times \text{factor}_{\text{y}}^{\text{fix}}$$

$$\text{cost}_{\text{line}}^{\text{fix}} = \sum_{y,z_s,z_o} C_{y,z_s,z_o}^{\text{line-fix}} \times \text{cap}_{\text{y,z}_\text{s}\text{,z}_\text{o}}^{\text{existing-line}} \times \text{factor}_{\text{y}}^{\text{fix}}$$

$$\text{cost}_{\text{tech}}^{\text{inv}} = \sum_{y,z,\text{e}} C_{y,z,\text{e}}^{\text{tech-inv}} \times \text{cap}_{\text{y,z,e}}^{\text{tech-inv}} \times \text{factor}_{\text{y}}^{\text{inv}}$$

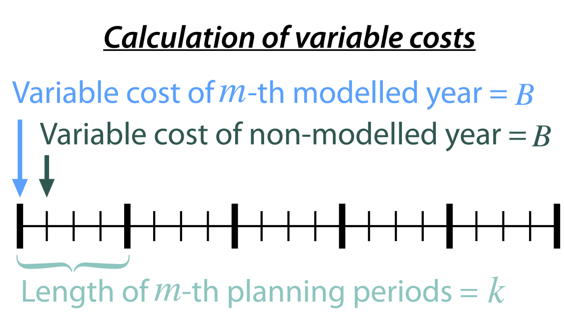
$$\text{cost}_{\text{line}}^{\text{inv}} = \sum_{y,z_s,z_o} C_{y,z_s,z_o}^{\text{line-inv}} \times \text{cap}_{\text{y,z}_\text{s}\text{,z}_\text{o}}^{\text{line-inv}} \times \text{factor}_{\text{y}}^{\text{inv}} \times 0.5$$

Factors

To account for the variable factor, fixed factor, and capital factor, we need to convert all future costs to their net present value. This means adjusting for the time value of money so that all costs are expressed in terms of today's dollars.

We also assume that variable cost and fixed cost for non-modelled years are assumed to be equal to the cost of the last modelled year preceding them. This allows for consistent comparison across different time periods and technologies.

Variable Factor



Given the following:

- Variable cost of modeled year: B
- Discount rate: r
- m-th modeled year: $m = y - y_{\text{min}}$
- Depreciation periods: n

The total present value can be calculated as follows:

$$\text{total present value} = \frac{B}{(1+r)^m} + \frac{B}{(1+r)^{m+1}} + \cdots + \frac{B}{(1+r)^{(m+k-1)}}$$

$$= B(1+r)^{(1-m)} \frac{1-(1+r)^k}{r}$$

And we can calculate the variable factor as follows:

$$\text{factor}_y^{var} = (1+r)^{1-m_y} \frac{1-(1+r)^{k_y}}{r}$$

$$m_y = y - y_{\text{min}}$$

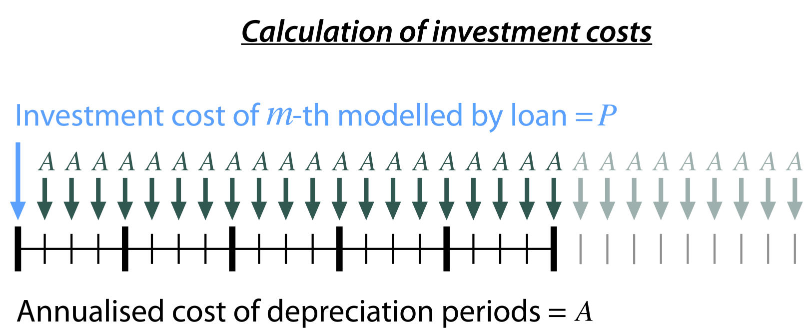
$$k_y = y_{\text{periods}}$$

Fixed Factor

We can equate the fixed factor with the variable factor as follows:

$$\text{factor}_y^{\text{fix}} = factor_y^{\text{var}}$$

Investment Factor



Given the following:

- Weighted Average Cost of Capital (WACC, or otherwise known as the interest rate): i
- Discount rate: r
- m-th modeled year: $m = y - y_{\text{min}}$
- Length of m-th planning periods: k

The total present value can be calculated as follows:

$$\text{total present value} = \frac{P}{(1+r)^m}$$

$$= \frac{\frac{A}{(1+i)} + \frac{A}{(1+i)^2} + \cdots + \frac{A}{(1+i)^n}}{(1+r)^m}$$

$$= A\frac{1-(1+i)^{-n}}{i} \times \frac{1}{(1+r)^m}$$

From the above, we can solve for the annualized cost of depreciation periods, A, as:

$$A = P\frac{i}{1-(1+i)^{-n}}$$

The capital recovery factor is then calculated as:

$$\text{capital recovery factor} = \frac{i}{1-(1+i)^{-n}}$$

Let's focus on the time periods that fall within the modelled time horizon (indicated in black colour). We can calculate the length of time periods, k, as follows:

$$k = y_{max} - y$$

Using k, we can calculate the net present value as follows:

$$\text{net present value} = \begin{cases} \frac{\frac{A}{(1+r)} + \frac{A}{(1+r)^2} + \cdots + \frac{A}{(1+r)^{min(n,k)}}}{(1+r)^m} & \text{if } n \leq k \\ \text{total present value} & \text{if } n > k \\ \frac{A\frac{1-(1+r)^{-k}}{r}}{(1+r)^m} = P\frac{i}{1-(1+i)^{-n}} \times \frac{1-(1+r)^{-k}}{r(1+r)^m} & \text{otherwise} \end{cases}$$

And we can calculate the investment factor as follows:

$$factor_y^{inv} = \frac{i}{1-(1+i)^{-n}} \times \frac{1-(1+r)^{-min(n,k)}}{r(1+r)^m}$$

4.4.6 Constraints

Retirement

The model computes the retirement of each technology and transmission line with these considerations:

- The historical capacity of the technology and transmission line is based on its capacity ratio.
- Each planning and scheduling period is based on the existing capacity.

The existing capacity for each year, in each zone, for each technology, is as follows:

$$\mathrm{cap}_{y,z,e}^{\mathrm{existingtech}} = \sum_{\mathrm{age}=1}^{T_e-(y-y_{\mathrm{start}})} \mathrm{CAP}_{\mathrm{age},z,e}^{\mathrm{inittech}} + \sum_{y_{\mathrm{pre}}=\max(y_{\mathrm{start}},y-T_e)}^{y} \mathrm{cap}_{y_{\mathrm{pre}},z,e}^{\mathrm{invtech}} \quad \forall y,z,e$$

The existing capacity of the transmission lines for each year, from z_{from} zone to z_{to}-th zone, is as follows:

$$\mathrm{cap}_{y,z_{\mathrm{from}},z_{\mathrm{to}}}^{\mathrm{existingline}} = \sum_{\mathrm{age}=1}^{T_{\mathrm{line}}-(y-y_{\mathrm{start}})} \mathrm{CAP}_{\mathrm{age},z_{\mathrm{from}},z_{\mathrm{to}}}^{\mathrm{initline}} + \sum_{y_{\mathrm{pre}}=\max(y_{\mathrm{start}},y-T_{\mathrm{line}})}^{y} \mathrm{cap}_{y_{\mathrm{pre}},z_{\mathrm{from}},z_{\mathrm{to}}}^{\mathrm{invline}} \quad \forall y, z_{\mathrm{from}} \neq z_{\mathrm{to}}$$

Carbon Emission

The model computes the carbon emissions for each year, based on the sum of carbon emissions from each zone, and from each technology as follows:

$$\mathrm{carbon}_y = \sum_{e\in\mathcal{E}}\sum_{z\in\mathcal{Z}}\sum_{m\in\mathcal{M}}\sum_{h\in\mathcal{H}} \left(\mathrm{CARBON}_{y,z,e} \times \mathrm{gen}_{h,m,y,z,e}\right) \quad \forall y$$

The calculated carbon emission for each year lower than its upper bound, as follows:

$$\mathrm{carbon}_y \leq \overline{\mathrm{CARBON}}_y \quad \forall y$$

Power Balance

The model computes the power balance for each hour, in each time period, for each year, and in each zone, as follows:

$$\mathrm{DEMAND}_{h,m,y,z} \times \Delta h = \sum_{z_{\mathrm{from}}\in\mathcal{Z}\setminus\{z\}} \mathrm{import}_{h,m,y,z_{\mathrm{from}},z} - \sum_{z_{\mathrm{to}}\in\mathcal{Z}\setminus\{z\}} \mathrm{export}_{h,m,y,z,z_{\mathrm{to}}}$$

$$+ \sum_{e\in\mathcal{E}} \mathrm{gen}_{h,m,y,z,e} - \sum_{e\in\mathcal{STOR}} \mathrm{charge}_{h,m,y,z,e} \quad \forall h,m,y,z$$

Transmission

We simplify the transmission of electricity as a transportation model. The model computes the transmission loss for each hour, in each time period, for each year, from z_{from} zone to z_{to} zone, as follows:

$$\mathrm{import}_{h,m,y,z_{\mathrm{from}},z_{\mathrm{to}}} = \mathrm{export}_{h,m,y,z_{\mathrm{from}},z_{\mathrm{to}}} \times \eta_{z_{\mathrm{from}},z_{\mathrm{to}}}^{\mathrm{trans}} \quad \forall h,m,y,z_{\mathrm{from}} \neq z_{\mathrm{to}}$$

This model assumes that the transmitted power of each transmission line is only constrained by the transmission capacity between two zones as follows:

$$\mathrm{import}_{h,m,y,z_{\mathrm{from}},z_{\mathrm{to}}} \leq \mathrm{cap}_{y,z_{\mathrm{from}},z_{\mathrm{to}}}^{\mathrm{existingline}} \times \Delta h \quad \forall h,m,y,z_{\mathrm{from}} \neq z_{\mathrm{to}}$$

$$\mathrm{export}_{h,m,y,z_{\mathrm{from}},z_{\mathrm{to}}} \leq \mathrm{cap}_{y,z_{\mathrm{from}},z_{\mathrm{to}}}^{\mathrm{existingline}} \times \Delta h \quad \forall h,m,y,z_{\mathrm{from}} \neq z_{\mathrm{to}}$$

Power Output

The power output of storage and each dispatchable (exclude hydropower) technology ($\text{power}_{h,m,y,z,e}$) is limited by the existing installed capacity ($\text{cap}^{\text{existingtech}}_{y,z,e}$) and minimum technical output, as follows:

$$\underline{\text{POWER}}_{h,m,y,z,e} \times \text{cap}^{\text{existingtech}}_{y,z,e} \le \text{power}_{h,m,y,z,e} \le \text{cap}^{\text{existingtech}}_{y,z,e} \quad \forall h,m,y,z,e \in \mathcal{STOR}\ \&\ \mathcal{DISP}$$

Since hydropower processes are explicitly modelled at the plant level in PREP-SHOT, total hydropower output in zone z ($\text{power}_{h,m,y,z,e=\text{hydro}}$) is the sum of the plant-level hydropower output ($\text{power}^{\text{hydro}}_{s,h,m,y}$):

$$\text{power}_{h,m,y,z,e=\text{hydro}} = \sum_{s\ \in \mathcal{SZ}_z} \text{power}^{\text{hydro}}_{s,h,m,y} \quad \forall h,m,y,z$$

Here, calculation of $\text{power}^{\text{hydro}}_{s,h,m,y}$ is obtained by external net water head simulation procedure. In addition, $\text{power}^{\text{hydro}}_{s,h,m,y}$ is bounded between the guaranteed minimum output ($\underline{\text{POWER}}^{\text{hydro}}_s$) and the nameplate capacity ($\text{CAP}^{\text{hydro}}_s$), as follows:

$$\underline{\text{POWER}}^{\text{hydro}}_s \le \text{power}^{\text{hydro}}_{s,h,m,y} \le \text{CAP}^{\text{hydro}}_s \quad \forall s,h,m,y$$

For VRE, their power output is constrained by the capacity factors as follows:

$$\text{power}_{h,m,y,z,e} \le \text{CF}_{h,m,y,z,e} \times \text{cap}^{\text{existingtech}}_{y,z,e} \quad \forall h,m,y,z,e \in \mathcal{NDISP}$$

Regardless of the technology type, actual power generation ($\text{gen}_{h,m,y,z,e}$) in a corresponding period Δh can be calculated based on the power output ($\text{power}_{h,m,y,z,e}$) and the generation efficiency ($\eta^{\text{out}}_{y,e}$):

$$\text{gen}_{h,m,y,z,e} = \text{power}_{h,m,y,z,e} \times \Delta h \times \eta^{\text{out}}_{y,e} \quad \forall h,m,y,z,e \in \mathcal{E}$$

Note that $\eta^{\text{out}}_{y,e} = 1$ when $e \in \mathcal{E} \backslash \mathcal{STOR}$.

Power output variation

All technologies apart from non-dispatchable technology are limited by the so-called ramping capability, meaning that the variation of their power output in two successive periods is limited. We introduce two non-negative auxiliary variables: increment ($\text{power}^{\text{up}}_{h,m,y,z,e}$) and decrement ($\text{power}^{\text{down}}_{h,m,y,z,e}$) to describe changes in power output in two successive periods (from h-1 to h) as follows:

$$\text{power}^{\text{up}}_{h,m,y,z,e} - \text{power}^{\text{down}}_{h,m,y,z,e} = \text{power}_{h,m,y,z,e} - \text{power}_{h-1,m,y,z,e} \quad \forall h,m,y,z,e\ \in \mathcal{E} \backslash \mathcal{NDISP}$$

When the power plant ramps up from h-1 to h, the minimum of $\text{power}^{\text{up}}_{h,m,y,z,e}$ is obtained when $\text{power}^{\text{down}}_{h,m,y,z,e}$ becomes zero. Similarly, when the power plant ramps down from h-1 to h, the minimum of $\text{power}^{\text{down}}_{h,m,y,z,e}$ is obtained when $\text{power}^{\text{up}}_{h,m,y,z,e}$ becomes zero. Therefore, we can constrain the maximum ramping up and down respectively, as follows:

$$\text{power}^{\text{up}}_{h,m,y,z,e} \le R^{\text{up}}_e \times \Delta h \times \text{cap}^{\text{existingtech}}_{y,z,e} \quad \forall h,m,y,z,e \in \mathcal{E} \backslash \mathcal{NDISP}$$

$$\text{power}^{\text{down}}_{h,m,y,z,e} \le R^{\text{down}}_e \times \Delta h \times \text{cap}^{\text{existingtech}}_{y,z,e} \quad \forall h,m,y,z,e \in \mathcal{E} \backslash \mathcal{NDISP}$$

where R^{up}_e/R^{down}_e is the allowed maximum/minimum ramping up/down capacity of technology e in two successive periods, expressed as a percentage of the existing capacity of storage technology e.

Energy storage

Similar to the power discharging process, the charging power of storage technology e ($\mathrm{power}^c_{h,m,y,z,e}$) is also limited by the existing installed capacity and technical minimum charging power ($\underline{\mathrm{POWER}}^c_{h,m,y,z,e}$) as follows:

$$\underline{\mathrm{POWER}}^c_{h,m,y,z,e} \times \mathrm{cap}^{\mathrm{existingtech}}_{y,z,e} \leq \mathrm{power}^c_{h,m,y,z,e} \leq \mathrm{cap}^{\mathrm{existingtech}}_{y,z,e} \quad \forall h, m, y, z, e \in \mathcal{STOR}$$

The charging generation ($\mathrm{charge}_{h,m,y,z,e}$) and $\mathrm{power}^c_{h,m,y,z,e}$ need to meet the following formula:

$$\mathrm{charge}_{h,m,y,z,e} = \mathrm{power}^{\mathrm{c}}_{h,m,y,z,e} \times \Delta h \times \eta^{\mathrm{in}}_{y,e} \quad \forall h, m, y, z, e \in \mathcal{STOR}$$

Changes in stored electricity ($\mathrm{storage}^{\mathrm{energy}}_{h,m,y,z,e}$) in two successive periods should be balanced by the charging ($\mathrm{charge}_{h,m,y,z,e}$) and discharging ($\mathrm{gen}_{h,m,y,z,e}$) processes:

$$\mathrm{storage}^{\mathrm{energy}}_{h,m,y,z,e} - \ \mathrm{storage}^{\mathrm{energy}}_{h-1,m,y,z,e} = \mathrm{charge}_{h,m,y,z,e} - \mathrm{gen}_{h,m,y,z,e}$$

In addition, the initial (when $h = h_{\mathrm{start}}$) stored electricity ($\mathrm{storage}^{\mathrm{energy}}_{h=h_{\mathrm{start}},m,y,z,e}$) of storage technology e in each month of each year can be calculated based on the proportion of the maximum storage capacity, as follows:

$$\mathrm{storage}^{\mathrm{energy}}_{h=h_{\mathrm{start}},m,y,z,e} = \mathrm{STORAGE}^{\mathrm{energy}}_{m,y,z,e} \times \mathrm{EP}_e \times \mathrm{cap}^{\mathrm{existingtech}}_{y,z,e} \quad \forall m, y, z, e \in \mathcal{STOR}$$

The instantaneous storage energy level ($\mathrm{storage}^{\mathrm{energy}}_{h,m,y,z,e}$) of storage technology e should not exceed the maximum energy storage capacity, as follows:

$$\mathrm{storage}^{\mathrm{energy}}_{h,m,y,z,e} \leq \mathrm{EP}_e \times \mathrm{cap}^{\mathrm{existingtech}}_{y,z,e} \quad \forall h, m, y, z, e \in \mathcal{STOR}$$

Water balance

Similar to the storage technologies, changes in reservoir storage ($\mathrm{storage}^{\mathrm{reservoir}}_{s,h,m,y}$) in two successive periods should be balanced by total inflow ($\mathrm{inflow}^{\mathrm{total}}_{s,h,m,y}$) and total outflow ($\mathrm{outflow}^{\mathrm{total}}_{s,h,m,y}$):

$$\mathrm{storage}^{\mathrm{reservoir}}_{s,h,m,y} - \mathrm{storage}^{\mathrm{reservoir}}_{s,h-1,m,y} = \Delta h \times 3600 \times \left(\mathrm{inflow}^{\mathrm{total}}_{s,h,m,y} - \mathrm{outflow}^{\mathrm{total}}_{s,h,m,y}\right) \quad \forall s, h, m, y$$

Here $\mathrm{inflow}^{\mathrm{total}}_{s,h,m,y}$ consists of two parts: the total outflow received from all immediate upstream reservoirs ($\sum_{\mathrm{su}\in\mathcal{IU}_s} \mathrm{outflow}^{\mathrm{total}}_{\mathrm{su},h-\tau_{\mathrm{su},s},m,y}$) and the net inflow (also called incremental inflow) of the drainage area controlled by this hydropower reservoir ($\mathrm{INFLOW}^{\mathrm{net}}_{s,h,m,y}$), which can be expressed as follows:

$$\mathrm{inflow}^{\mathrm{total}}_{s,h,m,y} = \mathrm{INFLOW}^{\mathrm{net}}_{s,h,m,y} + \sum_{\mathrm{su}\in\mathcal{IU}_s} \mathrm{outflow}^{\mathrm{total}}_{\mathrm{su},h-\tau_{\mathrm{su},s},m,y} \quad \forall s, h, m, y$$

Note that PREP-SHOT assumes a constant water travel (or propagation) time ($\tau_{\mathrm{su},s}$). The total outflow of each reservoir consists of three parts: upstream water withdrawal (i.e., water used for non-hydro purposes such as agriculture irrigation and urban water supply) ($\mathrm{outflow}^{\mathrm{withdraw}}_{s,h,m,y}$), generation flow (i.e., water flow through the turbines of the hydropower plant) ($\mathrm{outflow}^{\mathrm{gen}}_{s,h,m,y}$) and spillage flow (i.e., water spilled over the spillways) ($\mathrm{outflow}^{\mathrm{spillage}}_{s,h,m,y}$):

$$\mathrm{outflow}^{\mathrm{total}}_{s,h,m,y} = \mathrm{outflow}^{\mathrm{withdraw}}_{s,h,m,y} + \mathrm{outflow}^{\mathrm{gen}}_{s,h,m,y} + \mathrm{outflow}^{\mathrm{spillage}}_{s,h,m,y} \quad \forall s, h, m, y$$

Reservoir outflow

The generation flow and spillage flow of the reservoir are limited by the maximum outflow capacity of turbines ($\mathrm{OUTFLOW}^{\mathrm{gen}}_{s}$) and spillway ($\mathrm{OUTFLOW}^{\mathrm{spillage}}_{s}$), respectively. The sum of these two parts also needs to meet the minimum outflow required ($\mathrm{OUTFLOW}_{s}$) for other purposes (e.g., ecological flow, shipping flow). These constraints are summarized as:

$$\mathrm{outflow}^{\mathrm{gen}}_{s,h,m,y} \leq \mathrm{OUTFLOW}^{\mathrm{gen}}_{s} \quad \forall s,h,m,y$$

$$\mathrm{outflow}^{\mathrm{spillage}}_{s,h,m,y} \leq \mathrm{OUTFLOW}^{\mathrm{spillage}}_{s} \quad \forall s,h,m,y$$

$$\mathrm{OUTFLOW}_{s} \leq \mathrm{outflow}^{\mathrm{gen}}_{s,h,m,y} + \mathrm{outflow}^{\mathrm{spillage}}_{s,h,m,y} \quad \forall s,h,m,y$$

Reservoir storage

The initial (when $h = h_{\mathrm{start}}$) and terminal (when $h = h_{\mathrm{end}}$) storage ($\mathrm{storage}^{\mathrm{reservoir}}_{s,h=h_{\mathrm{start}},m,y}$ and $\mathrm{storage}^{\mathrm{reservoir}}_{s,h=h_{\mathrm{end}},m,y}$) of hydropower reservoir in each month of each year should be assigned as:

$$\mathrm{storage}^{\mathrm{reservoir}}_{s,h=h_{\mathrm{start}},m,y} = \mathrm{STORAGE}^{\mathrm{initreservoir}}_{s,m,y} \quad \forall s,m,y$$

$$\mathrm{storage}^{\mathrm{reservoir}}_{s,h=h_{\mathrm{end}},m,y} = \mathrm{STORAGE}^{\mathrm{endreservoir}}_{s,m,y} \quad \forall s,m,y$$

The reservoir storage is bounded between the maximum ($\overline{\mathrm{STORAGE}^{\mathrm{reservoir}}_{s}}$) and minimum storage ($\underline{\mathrm{STORAGE}^{\mathrm{reservoir}}_{s}}$) depending on the functions (e.g., flood control, recreation, and water supply) of the reservoir:

$$\underline{\mathrm{STORAGE}^{\mathrm{reservoir}}_{s}} \leq \mathrm{storage}^{\mathrm{reservoir}}_{s,h,m,y} \leq \overline{\mathrm{STORAGE}^{\mathrm{reservoir}}_{s}} \quad \forall s,h,m,y$$

4.5 Forum

We encourage our community to actively participate and engage in discussions. The diverse perspectives and feedback from our users are valuable to us and will help us improve the model and its documentation.

Check out the FAQ page for answers to common questions.

4.5.1 GitHub Discussions

Users can join us for public discussions on the Discussions page in our GitHub repository.

- Ask questions or seek clarifications.
- Share ideas or best practices.
- Showcase how you have used the model for your projects and share your experiences.
- Engage in constructive conversations with our community.

4.5.2 Private Queries

If you have specific questions, feedback, or topics that are not suitable for public discussions, you may directly reach out to Zhanwei Liu.

4.6 Changelog

Here, you'll find notable changes for each version of PREP-SHOT.

4.6.1 Version 0.1 - Oct 15, 2023

Initial Release:

- PREP-SHOT model is released with basic functionality for energy expansion planning.
- Linear programming optimization model for energy systems with multiple zones.
- Support for solvers such as Gurobi, CPLEX, MOSEK, and GLPK via Pyomo.
- Input and output handling with *pandas* and *Xarray*.

4.6.2 Contributing to PREP-SHOT

We welcome and appreciate contributions from the community. Here are the steps to contribute:

1. **Create an Issue**

   If you find a bug or have an idea for an improvement or new feature, please create an issue.

2. **Fork the Repository**

   You can fork the PREP-SHOT repository on GitHub.

3. **Create a Branch**

   Create a new branch in your forked repository and name the branch according to the feature or fix you're working on.

4. **Commit Changes**

   Make changes in your branch. Once you've made improvements or bug fixes to the project, commit the changes with a meaningful commit message.

5. **Start a Pull Request**

   Open a pull request from your forked repository to the main PREP-SHOT repository. Describe your changes in the pull request.

6. **Code Review**

   Maintainers of the PREP-SHOT project will review your code. They may ask for changes or improvements before the code is merged into the main codebase.

Please ensure that you update tests as necessary when you're contributing code, and follow the coding conventions established in the rest of the project.

4.7 References

BIBLIOGRAPHY

[1] Zhanwei Liu and Xiaogang He. Balancing-oriented hydropower operation makes the clean energy transition more affordable and simultaneously boosts water security. *Nature Water*, 1:778–789, 2023. doi:10.1038/s44221-023-00126-0.

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