openTEPES

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Open Generation, Storage, and **T**ransmission Operation and **E**xpansion **P**lanning Model with RES and **ES**S (**openTEPES**)

"*Simplicity and Transparency in Energy Systems Planning*"

The **openTEPES** model has been developed at the Instituto de Investigación Tecnológica (IIT) of the Universidad Pontificia Comillas.

The **openTEPES** model presents a decision support system for defining the integrated generation, storage, and transmission expansion plan (GEP+SEP+TEP) -**Integrated Resource Planning** (IRP)- of a **large-scale electric system** at a tactical level (i.e., time horizons of 5-30 years), defined as a set of **generation, storage, and (electricity, hydrogen, and heat) networks dynamic investment decisions for multiple future years**.

It is integrated into the open energy system modelling platform, helping model Europe's energy system and in the list of energy models published under open source licenses. It is also part of the Africa open energy system modelling toolbox, which is a suite of open and linked state-of-the-art open-source energy system models for Africa.

Scripts are provided to exchange information with Integrated Assessment Models (IAM) using their nomenclature and data formats.

It has been used by the **Ministry for the Ecological Transition and the Demographic Challenge (MITECO)** to analyze the electricity sector in the latest Spanish National Energy and Climate Plan (NECP) Update 2023-2030 in September 2024.

Reference: A. Ramos, E. Quispe, S. Lumbreras "OpenTEPES: Open-source Transmission and Generation Expansion Planning" SoftwareX 18: June 2022 10.1016/j.softx.2022.101070

openTEPES: summary presentation (English), présentation (French), and installation guide

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openTEPES GitHub repository

CHAPTER

ONE

INTRODUCTION

The *Open Generation, Storage, and Transmission Operation and Expansion Planning Model with RES and ESS* **(openTEPES)** determines the investment plans of new facilities (generators, ESS, and electric lines, hydrogen pipelines, and heat pipes) to meet the forecasted demand at minimum cost. The objective is to evaluate the future generation, storage, and electric, hydrogen, and heat network needs. The main results are the guidelines for the future structure of the generation, storage, and transmission systems.

The **openTEPES** model represents a decision support system for defining the **integrated generation, storage, and transmission resource planning** (IRP, GEP+SEP+TEP) of a **large-scale electric system** at the tactical level (i.e., time horizons of 10-20 years), defined as a set of **generation, storage, and (electricity, hydrogen, and heat) networks dynamic investment decisions for several future years**. The user pre-defines the expansion candidates, so the model determines the optimal decisions among those specified by the user.

It automatically determines optimal expansion plans that satisfy multiple attributes simultaneously. Its main features are:

- **Dynamic (perfect foresight)**: the scope of the model corresponds to several periods (years) on a long-term horizon, for example 2030, 2035 and 2040.

  It hierarchically represents the different time horizons for decision making in an electricity system:

  - Load level: one hour, e.g., 01-01 00:00:00+01:00 to 12-30 23:00:00+01:00

  Time division allows a user-defined flexible representation of time periods for evaluating system operation. It can also be run with chronological periods of several consecutive hours (two-hour, three-hour resolution) to reduce the computational burden without sacrificing accuracy. The model can be run with a single period (year) or with multiple periods (years) to allow analysis of system evolution. The time definition also allows the specification of disconnected representative periods (e.g., days, weeks) to evaluate system operation. The model can be run with a single period (year) or with multiple periods (years) to allow analysis of system evolution. The time definition can also specify unrelated representative periods (e.g., days, weeks) to evaluate system operation. The period (year) must be represented by 8736 hours because several model concepts representing the system operation are based on weeks (168 hours) or months (made of 4 weeks, 672 hours)

- **Stochastic**: several stochastic parameters are considered that can influence the optimal generation, storage and transmission expansion decisions. The model considers stochastic medium-term annual uncertainties (scenarios) related to the system operation. These operational scenarios are associated with renewable energy sources, energy inflows and outflows, natural water inflows, operating reserves, inertia, and electricity, hydrogen, and heat demand.

The objective function includes the two main quantifiable costs: the **investment costs for generation, storage, and transmission (CAPEX)** and the **expected variable operation costs (including generation, consumption, emissions, and reliability costs) (system OPEX)**.

The model formulates a **two-stage stochastic optimization** problem, including binary generation, storage, and electricity, hydrogen, and heat network investment/retirement decisions, generation operation decisions (commitment, startup, and shutdown decisions are also binary), and electric line-switching decisions. Capacity expansion takes into account the adequacy system reserve margin, maximum CO2 emissions, and minimum and maximum energy constraints.

The highly detailed operation model is an electric **network-constrained unit commitment (NCUC)** based on a **tight and compact** formulation, including **operating reserves** with a **DC power flow (DCPF)**, including electric **line-switching** decisions. The **ohmic losses of the electricity network** are considered proportional to the electric line flow. It considers different **energy storage systems (ESS)**, such us pumped-hydro storage, battery, demand response, electric vehicles, solar thermal, electrolyzer, etc. It allows analysis of the trade-off between the investment in generation/transmission/pipeline and the investment and/or use of storage capacity.

The model also allows a representation of the **hydro system** based on volume and water inflow data considering the water stream topology (hydro cascade basins). If they are not available it runs with an energy-based representation of the hydro system.

Also, it includes a representation of **Power to Hydrogen (P2H2)** by setting the **hydrogen demand** satisfied by the production of hydrogen with electrolyzers (consume electricity to produce hydrogen) and a **hydrogen network** to distribute it. Besides, it includes a representation of **Power to Heat (P2H)** by setting the **heat demand** satisfied by the production of heat with heat pumps or electric heater (consume electricity to produce heat) and a **heat network** to distribute it. If they are not available it runs with just the other energy carriers.

The main results of the model can be structured in these topics:

- **Investment**: (generation, storage, hydro reservoirs, electric lines, hydrogen pipelines, and heat pipes) investment decisions and cost
- **Operation**: unit commitment, startup, and shutdown of non-renewable units, unit output and aggregation by technologies (thermal, storage hydro, pumped-hydro storage, RES), RES curtailment, electric line, hydrogen pipeline, and heat pipe flows, line ohmic losses, node voltage angles, upward and downward operating reserves, ESS inventory levels, hydro reservoir volumes, power, hydrogen, and heat not served
- **Emissions**: CO2 emissions by unit
- **Marginal**: Locational Short-Run Marginal Costs (LSRMC), stored energy value, water volume value
- **Economic**: operation, emission, and reliability costs and revenues from operation and operating reserves
- **Flexibility**: flexibility provided by demand, by the different generation and consumption technologies, and by power not served

Results are shown in csv files and graphical plots.

openTEPES is being used by investors, market participants, system planners, and consultants. A careful implementation has been done to avoid numerical problems by scaling parameters, variables and equations of the optimization problem allowing the model to be used for very large-scale cases, e.g., the European system with hourly detail. For example, a European operation case study with hourly detail has reached 39.7 million constraints and 34.7 million variables of an LP problem. The mainland Spain operation case has reached 5.2 million constraints and 6.8 million variables (1.3 million binary).

CHAPTER

TWO

ELECTRIC SYSTEM INPUT DATA

All the input files must be located in a folder with the name of the case study.

2.1 Acronyms

Acronym	Description
AC	Alternating Current
aFRR	Automatic Frequency Restoration Reserve
AWE	Alkaline Water Electrolyzer (consumes electricity to produce hydrogen)
BESS	Battery Energy Storage System
CC	Capacity Credit
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power. Cogeneration (produces electricity and heat simultaneously)
DC	Direct Current
DCPF	DC Optimal Power Flow
DR	Demand Response
DSM	Demand-Side Management (e.g., load shifting)
DSR	Demand-Side Response (e.g., interruptibility)
EB	Electric Boiler
EHU	Electrical Heating Unit (Power to Heat: consumes electricity to produce heat, e.g., heat pump, electric boiler)
EFOR	Equivalent Forced Outage Rate
ELZ	Electrolyzer (Power to Hydrogen: consumes electricity to produce hydrogen)
ENS	Energy Not Served
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage System
EV	Electric Vehicle
FHU	Fuel Heating Unit (Fuel to Heat: consumes any fuel other than hydrogen to produce heat, e.g., biomass/natural gas/oil bo
GEP	Generation Expansion Planning
mFRR	Manual Frequency Restoration Reserve
H2	Hydrogen
HHU	Hydrogen Heating unit (Hydrogen to Heat: consumes hydrogen to produce heat)
HNS	Hydrogen Not Served
HP	Heat Pump (power to heat: consumes electricity to produce heat)
HTNS	Heat Not Served
IRP	Integrated Resource Planning
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PHS	Pumped-Hydro Storage
PNS	Power Not Served

CO

Table 1 – continued from previous page

Acronym	Description
PTDF	Power Transfer Distribution Factor
PV	Photovoltaics
RES	Renewable Energy Source
SEP	Storage Expansion Planning
TEP	Transmission Expansion Planning
TTC	Total Transfer Capacity
VoLL	Value of Lost Load
VRE	Variable Renewable Energy
VRES	Variable Renewable Energy Source (units with null linear variable cost and no storage capacity. Do not contribute to the

2.2 Dictionaries. Sets

The dictionaries include all the possible elements of the corresponding sets included in the optimization problem. **You can't use non-English characters (e.g., ó, º)**

File	Description
oT_Dict_ csv	Period (e.g., 2030, 2035). **It must be a positive integer**
oT_Dict_ csv	Scenario. Short-term uncertainties (scenarios) (e.g., s001 to s100, CY2025 to CY2030)
oT_Dict_ csv	Stage
oT_Dict_ csv	Load level (e.g., 01-01 00:00:00+01:00 to 12-30 23:00:00+01:00). If is a datetime format. Load levels with duration 0 are ignored. The period (year) must represented by 8736 load levels.
oT_Dict_ csv	Generation units (thermal -nuclear, CCGT, OCGT, coal-, ESS -storage hydro modeled in energy or in water, pumped-hydro storage PHS, battery BESS, electric vehicle EV, demand side management DSM, alkaline water electrolyzer AWE, solar thermal- and VRES -wind onshore and offshore, solar PV, run-of-the-river hydro-)
oT_Dict_ csv	Generation technologies. The technology order is used in the temporal result plot.
oT_Dict_ csv	ESS storage type (daily <12 h, weekly <40 h, monthly >60 h).
oT_Dict_ csv	Nodes. A node belongs to a zone.
oT_Dict_ csv	Zones. A zone belongs to an area.
oT_Dict_ csv	Areas. An area belongs to a region. Long-term adequacy, inertia and operating reserves are associated to areas.
oT_Dict_ csv	Regions
oT_Dict_ csv	Circuits
oT_Dict_ csv	Line type (AC, DC)

Geographical location of nodes, zones, areas, regions.

File	Dictionary	Description
`oT_Dict_NodeToZone.csv`	NodeToZone	Location of nodes at zones
`oT_Dict_ZoneToArea.csv`	ZoneToArea	Location of zones at areas
`oT_Dict_AreaToRegion.csv`	AreaToRegion	Location of areas at regions

See the hydropower system section at the end of this page to know how to define the basin topology (connection among reservoir and hydropower plants). Some additional dictionaries and data files are needed.

2.3 Input files

This is the list of the input data files and their brief description.

File	Description
oT_Data_Option.csv	Options of use of the **openTEPES** model
oT_Data_Parameter.csv	General system parameters
oT_Data_Period.csv	Weight of each period
oT_Data_Scenario.csv	Short-term uncertainties
oT_Data_Stage.csv	Weight of each stage
oT_Data_ReserveMar csv	Minimum adequacy reserve margin for each area and period
oT_Data_Emission.csv	Maximum CO2 emissions of the electric system
oT_Data_RESEnergy.csv	Minimum RES energy
oT_Data_Duration.csv	Duration of the load levels
oT_Data_Demand.csv	Electricity demand
oT_Data_Inertia.csv	System inertia by area
oT_Data_OperatingR csv	Upward operating reserves (include aFRR and mFRR for electricity balancing from ENTSO-E)
oT_Data_OperatingR csv	Downward operating reserves (include aFRR and mFRR for electricity balancing from ENTSO-E)
oT_Data_Generation csv	Generation (electricity and heat) data
oT_Data_VariableMa csv	Variable maximum power generation by load level
oT_Data_VariableMi csv	Variable minimum power generation by load level
oT_Data_VariableMa csv	Variable maximum power consumption by load level
oT_Data_VariableMi csv	Variable minimum power consumption by load level
oT_Data_VariableFu csv	Variable fuel cost by load level
oT_Data_EnergyInfl csv	Energy inflows into an ESS by load level
oT_Data_EnergyOutf csv	Energy outflows from an ESS for Power-to-X (H2 production, EV mobility, heat production, or water irrigation) by load level
oT_Data_VariableMa csv	Maximum amount of energy stored in the ESS (defined per load level)
oT_Data_VariableMi csv	Minimum amount of energy stored in the ESS (defined per load level)
oT_Data_VariableMa csv	Maximum amount of energy produced/consumed by the unit by time interval (the amount of energy considered corresponds to the aggregate over the interval defined by EnergyType)
oT_Data_VariableMi csv	Minimum amount of energy produced/consumed by the unit by time interval (the amount of energy considered corresponds to the aggregate over the interval defined by EnergyType)
oT_Data_Network.csv	Electricity network data
oT_Data_VariableTT csv	Maximum electric transmission line TTC forward flow (defined per load level) (optional file)
oT_Data_VariableTT csv	Maximum electric transmission line TTC backward flow (defined per load level) (optional file)
oT_Data_NodeLocati csv	Node location in latitude and longitude

In any input file only the columns indicated in this document will be read. For example, you can add a column for comments or additional information as needed, but it will not read by the model.

2.4 Options

A description of the options included in the file `oT_Data_Option.csv` follows:

Item	Description	
IndBinGenInvest	Indicator of binary generation expansion decisions	{0 continuous, 1 binary, 2 ignore investments}
IndBinGenRetirement	Indicator of binary generation retirement decisions	{0 continuous, 1 binary, 2 ignore retirements}
IndBinRsrInvest	Indicator of binary reservoir expansion decisions (only used for reservoirs modeled with water units)	{0 continuous, 1 binary, 2 ignore investments}
IndBinNetInvest	Indicator of binary electricity network expansion decisions	{0 continuous, 1 binary, 2 ignore investments}
IndBinNetH2Invest	Indicator of binary hydrogen network expansion decisions	{0 continuous, 1 binary, 2 ignore investments}
IndBinNetHeatInvest	Indicator of binary heat network expansion decisions	{0 continuous, 1 binary, 2 ignore investments}
IndBinGenOperat	Indicator of binary generation operation decisions	{0 continuous, 1 binary}
IndBinGenRamps	Indicator of considering or not the up/down ramp constraints	{0 no ramps, 1 ramp constraints}
IndBinGenMinTime	Indicator of considering or not the min up/down time constraints	{0 no min time constraints, 1 min time constraints}
IndBinSingleNode	Indicator of single node case study	{0 network, 1 single node}
IndBinLineCommit	Indicator of binary transmission switching decisions	{0 continuous, 1 binary}
IndBinNetLosses	Indicator of network losses	{0 lossless, 1 ohmic losses}

If the investment decisions are ignored (IndBinGenInvest, IndBinGenRetirement, and IndBinNetInvest take value 2) or there are no investment decisions, all the scenarios with a probability >0 are solved sequentially (assuming a probability 1) and the periods are considered with a weight 1.

2.5 Parameters

A description of the system parameters included in the file `oT_Data_Parameter.csv` follows:

Item	Description	
ENSCost	Cost of energy not served (ENS). Cost of load curtailment. Value of Lost Load (VoLL)	€/MWh
HNSCost	Cost of hydrogen not served (HNS)	€/kgH2
HTNSCost	Cost of heat not served (HTNS)	€/MWh
PNSCost	Cost of power not served (PNS) associated with the deficit in operating reserve by load level	€/MW
CO2Cost	Cost of CO2 emissions	€/tCO2
UpReserveActivation	Upward reserve activation (proportion of upward operating reserve deployed to produce energy, e.g., 0.3)	p.u.
DwReserveActivation	Downward reserve activation (proportion of downward operating reserve deployed to produce energy, e.g., 0.25)	p.u.
MinRatioDwUp	Minimum ratio downward to upward operating reserves	p.u.
MaxRatioDwUp	Maximum ratio downward to upward operating reserves	p.u.
Sbase	Base power used in the DCPF	MW
ReferenceNode	Reference node used in the DCPF	
TimeStep	Duration of the time step for the load levels (hourly, bi-hourly, trihourly, etc.)	h
EconomicBaseYear	Base year for economic parameters affected by the discount rate	year
AnnualDiscountRate	Annual discount rate	p.u.

A time step greater than one hour it is a convenient way to reduce the load levels of the time scope. The moving average of the demand, upward/downward operating reserves, variable generation/consumption/storage and ESS energy inflows/outflows over the time step load levels is assigned to active load levels (e.g., the mean value of the three hours is associated to the third hour in a trihourly time step).

2.6 Period

A description of the data included in the file `oT_Data_Period.csv` follows:

Identifier	Header	Description
Period	Weight	Weight of each period

This weight allows the definition of equivalent (representative) years (e.g., year 2030 with a weight of 5 would represent years 2030-2034). Periods are not mathematically connected between them with operation constraints, i.e., no constraints link the operation at different periods. However, they are linked by the investment decisions, i.e., investments made in a year remain installed for the rest of the years.

2.7 Scenario

A description of the data included in the file `oT_Data_Scenario.csv` follows:

Identifiers		Header	Description	
Period	Scenario	Probability	Probability of each scenario in each period	p.u.

For example, the scenarios can be used for obtaining the IRP (GEP+SEP+TEP) considering hydro energy/water inflows uncertainty represented by means of three scenarios (wet, dry and average), or two VRES scenarios (windy/cloudy and calm/sunny). The sum of the probabilities of all the scenarios of a period must be 1.

2.8 Stage

A description of the data included in the file `oT_Data_Stage.csv` follows:

Identifier	Header	Description
Scenario	Weight	Weight of each stage

This weight allows the definition of equivalent (representative) periods (e.g., one representative week with a weight of 52 or four representative weeks each one with a weight of 13). Stages are not mathematically connected between them, i.e., no constraints link the operation at different consecutive stages. Therefore, the storage type can't exceed the duration of the stage (i.e., if the stage lasts for 168 hours the storage type can only be hourly or daily). If there are no investment decisions or the investment decisions are ignored, all the periods, scenarios, and stages are solved independently.

2.9 Adequacy reserve margin

The adequacy reserve margin is the ratio between the available capacity and the maximum demand. According to ENTSO-e, adequacy is defined as the ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. For determining the available capacity, the model uses the availability of the generating units times their maximum power. The availability can be computed as the ratio between the firm capacity and the installed capacity. Firm capacity can be determined as the Firm Capacity Equivalent (FCE) or the Effective Load-Carrying Capability (ELCC). A description of the data included in the file `oT_Data_ReserveMargin.csv` follows:

Identifiers		Header	Description	
Period	Area	ReserveMargin	Minimum adequacy reserve margin for each period and area	p.u.

This parameter is only used for system generation expansion, not for the system operation. If no value is introduced for an area, the reserve margin is considered 0.

2.10 Maximum CO2 emissions

A description of the data included in the file `oT_Data_Emission.csv` follows:

Identifiers		Header	Description	
Period	Area	CO2Emission	Maximum CO2 emissions of the electric system for each period and area	MtCO2

If no value is introduced for an area, the CO2 emission limit is considered infinite.

2.11 Minimum RES energy

It is like a Renewable Portfolio Standard (RPS). A description of the data included in the file `oT_Data_RESEnergy.csv` follows:

Identifiers		Header	Description	
Period	Area	RESEnergy	Minimum RES energy for each period and area	GWh

If no value is introduced for an area, the RES energy limit is considered 0.

2.12 Duration

A description of the data included in the file `oT_Data_Duration.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLev	Duration Stage	Duration of the load level. Load levels with duration 0 are ignored Assignment of the load level to a stage	h

It is a simple way to use isolated snapshots or representative days or just the first three months instead of all the hours of a year to simplify the optimization problem. All the load levels must have the same duration. The duration is not intended to change for the several load levels of an stage. Usually, duration is put as 1 hour or 0 if you want not to use the load levels after some hour of the year. The parameter time step must be used to collapse consecutive load levels into a single one for the optimization problem.

The stage duration as sum of the duration of all the load levels must be larger or equal than the shortest duration of any storage type or any outflows type or any energy type (all given in the generation data) and multiple of it. Consecutive stages are not connected between them, i.e., no constraints link the operation at different stages. Consequently, the storage type can't exceed the duration of the stage (i.e., if the stage lasts for 168 hours the storage type can only be hourly or daily). Consequently, the objective function with several stages must be a bit higher than in the case of a single stage.

The initial storage of the ESSs is also fixed at the beginning and end of each stage. For example, the initial storage level is set for the hour 8736 in case of a single stage or for the hours 4368 and 4369 (end of the first stage and beginning of the second stage) in case of two stages, each with 4368 hours.

2.13 Electricity demand

A description of the data included in the file `oT_Data_Demand.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Node	Power demand of the node for each load level	MW

The electricity demand can be negative for the (transmission) nodes where there is (renewable) generation in lower voltage levels. This negative demand is equivalent to generate that power amount in this node. Internally, all the values below if positive demand (or above if negative demand) 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

2.14 System inertia

A description of the data included in the files `oT_Data_Inertia.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Area	System inertia of the area for each load level	s

Given that the system inertia depends on the area, it can be sensible to assign an area as a country, for example. The system inertia can be used for imposing a minimum synchronous power and, consequently, force the commitment of at least some rotating units. Each generating unit can contribute to the system inertia. The system inertia is the sum of the inertia of all the committed units in the area.

Internally, all the values below 1e-5 times the maximum system electricity demand of each area will be converted into 0 by the model.

2.15 Upward and downward operating reserves

A description of the data included in the files `oT_Data_OperatingReserveUp.csv` and `oT_Data_OperatingReserveDown.csv` follows:

Identifiers				Header Description	
Period	Scenario	LoadLevel	Area	Upward/downward operating reserves of the area for each load level	MW

Given that the operating reserves depend on the area, it can be sensible to assign an area as a country, for example. These operating reserves must include Automatic Frequency Restoration Reserves (aFRR) and Manual Frequency Restoration Reserves (mFRR) for electricity balancing from ENTSO-E.

Internally, all the values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

2.16 Generation

A description of the data included for each (electricity and heat) generating unit in the file `oT_Data_Generation.csv` follows:

Header	Description
Node	Name of the node where generator is located. If left empty, the generator is ignored
Technology	Technology of the generator (nuclear, coal, CCGT, OCGT, ESS, solar, wind, biomass, etc.)
MutuallyExclusive	List of mutually exclusive sets the generator belongs to. Only one generator per set can be committed
BinaryCommitment	Binary unit commitment decision
NoOperatingReserve	No contribution to operating reserve. Yes if the unit doesn't contribute to the operating reserve
OutflowsIncompatibility	Outflows are incompatible with the charging process (e.g., electric vehicle). This is not the case of an
StorageType	Represents the time period (hour, day, week, month, year) over which the requirement that aggregate
OutflowsType	Represents the time period (hour, day, week, month, year) over which the specified amount of energy
EnergyType	Represents the time period (hour, day, week, month, year) over which the specified max/min amount
MustRun	Must-run unit
InitialPeriod	Initial period (year) when the unit is installed or can be installed, if candidate
FinalPeriod	Final period (year) when the unit is installed or can be installed, if candidate
MaximumPower	Maximum power output of electricity (generation/discharge for ESS units)
MinimumPower	Minimum power output of electricity (i.e., minimum stable load in the case of a thermal power plant)
MaximumPowerHeat	Maximum heat output (heat produced by a CHP, at its maximum electric power, or by a fuel heater, w
MinimumPowerHeat	Minimum heat output (heat produced by a CHP, at its minimum electric power, or by a fuel heater, wi
MaximumReactivePower	Maximum reactive power output (discharge for ESS units) (not used in this version)
MinimumReactivePower	Minimum reactive power output (not used in this version)
MaximumCharge	Maximum consumption/charge level when the ESS unit is storing energy
MinimumCharge	Minimum consumption/charge level when the ESS unit is storing energy
InitialStorage	Initial amount of energy stored at the first instant of the time scope
MaximumStorage	Maximum amount of energy that can be stored by the ESS unit

Ta

Header	Description
MinimumStorage	Minimum amount of energy that can be stored by the ESS unit
Efficiency	Round-trip efficiency of the pump/turbine cycle of a pumped-hydro storage power plant or charge/dis
ProductionFunctionHydro	Production function from water inflows (denominator) to electricity (numerator) (only used for hydro
ProductionFunctionH2	Production function from electricity (numerator) to hydrogen (denominator) (only used for electrolyz
ProductionFunctionHeat	Production function from electricity (numerator) to heat (denominator) (only used for heat pumps or
ProductionFunctionH2ToHeat	Production function from hydrogen (numerator) to heat (denominator) (only used for hydrogen heate
Availability	Unit availability for area adequacy reserve margin (also called de-rating factor or capacity credit or F
Inertia	Unit inertia constant
EFOR	Equivalent Forced Outage Rate
RampUp	Maximum rate of increasing its output for generating units, or maximum rate of increasing its dischar
RampDown	Maximum rate of decreasing its output for generating units, or maximum rate of increasing its charge
UpTime	Minimum uptime
DownTime	Minimum downtime
StableTime	Minimum stable time (intended for nuclear units to be at its minimum load, if lower than the rated ca
ShiftTime	Maximum shift time
FuelCost	Fuel cost
LinearTerm	Linear term (slope) of the heat rate straight line
ConstantTerm	Constant term (intercept) of the heat rate straight line
OMVariableCost	Variable O&M cost
OperReserveCost	Operating reserve cost
StartUpCost	Startup cost
ShutDownCost	Shutdown cost
CO2EmissionRate	CO2 emission rate. It can be negative for units absorbing CO2 emissions as biomass
FixedInvestmentCost	Overnight investment (capital -CAPEX- and fixed O&M -FOM-) cost
FixedRetirementCost	Overnight retirement (capital -CAPEX- and fixed O&M -FOM-) cost
FixedChargeRate	Fixed-charge rate to annualize the overnight investment cost. Proportion of annual payment to return
StorageInvestment	Storage capacity and energy inflows linked to the investment decision
BinaryInvestment	Binary unit investment decision
InvestmentLo	Lower bound of investment decision
InvestmentUp	Upper bound of investment decision
BinaryRetirement	Binary unit retirement decision
RetirementLo	Lower bound of retirement decision
RetirementUp	Upper bound of retirement decision

The main characteristics that define each type of generator are the following:

Generator type	Description	Set name
Generator	It has MaximumPower or MaximumCharge or MaximumPowerHeat >0	*g*
Thermal	Fuel-based variable cost (fuel cost x linear term + CO2 emission cost) >0	*t*
VRE	Fuel-based variable cost (fuel cost x linear term + CO2 emission cost) =0 and MaximumStorage =0. It may have OMVariableCost >0	*re*
Non-renewable	All the generators except the RESS	*nr*
ESS	It has MaximumCharge or MaximumStorage >0 or ProductionFunctionH2 or ProductionFunctionHeat >0 and ProductionFunctionHydro =0	*es*
Hydro power plant (energy)	ESS with ProductionFunctionHydro =0	*es*
Pumped-hydro storage (energy)	ESS with MaximumCharge >0	*es*
Battery (BESS), load shifting (DSM)	ESS with MaximumCharge >0 (usually, StorageType daily)	*es*
Electric vehicle (EV)	ESS with electric energy outflows	*es*
Electrolyzer (ELZ)	ESS with electric energy outflows and ProductionFunctionH2 >0 and ProductionFunctionHeat =0 and ProductionFunctionHydro =0	*el*
Heat pump or electric boiler	ESS with ProductionFunctionHeat >0 and ProductionFunctionH2 =0 and ProductionFunctionHydro =0	*hp*
CHP or fuel heating unit	It has RatedMaxPowerElec >0 and RatedMaxPowerHeat >0 and ProductionFunctionHeat =0	*ch*
Fuel heating unit, fuel boiler	It has RatedMaxPowerElec =0 and RatedMaxPowerHeat >0 and ProductionFunctionHeat =0	*bo*
Hydrogen heating unit	Fuel heating unit with ProductionFunctionH2ToHeat >0	*hh*
Hydro power plant (water)	It has ProductionFunctionHydro >0	*h*

The model allways considers a month of 672 hours, i.e., 4 weeks, not calendar months. The model considers a year of 8736 hours, i.e., 52 weeks, not calendar years.

Daily *storage type* means that the ESS inventory is assessed every time step. For daily storage type it is assessed at the end of every hour, for weekly storage type it is assessed at the end of every day, monthly storage type is assessed at the end of every week, and yearly storage type is assessed at the end of every month. *Outflows type* represents when the energy extracted from the storage must be satisfied (for daily outflows type at the end of every day, i.e., the sum of the energy consumed must be equal to the sum of outflows daily). *Energy type* represents when the minimum or maximum energy to be produced by a unit must be satisfied (for daily energy type at the end of every day, i.e., the sum of the energy generated by the unit must be lower/greater than the sum of max/min energy for every day). The *storage cycle* is the minimum between the inventory assessment period (defined by the storage type), the outflows period (defined by the outflows type), and the energy period (defined by the energy type) (only if outflows or energy power values have been introduced). It can be one time step, one day, one week, and one month, but it can't exceed the stage duration. For example, if the stage lasts for 168 hours the storage cycle can only be hourly or daily.

The initial storage of the ESSs is also fixed at the beginning and end of each stage, only if the initial inventory lies between the storage limits. For example, the initial storage level is set for the hour 8736 in case of a single stage or for the hours 4368 and 4369 (end of the first stage and beginning of the second stage) in case of two stages, each with 4368 hours.

A generator with operation cost (sum of the fuel and emission cost, excluding O&M cost) >0 is considered a non-renewable unit. If the unit has no operation cost and its maximum storage =0, it is considered a renewable unit. If its maximum storage is >0, with or without operation cost, is considered an ESS.

A very small variable O&M cost (not below 0.01 €/MWh, otherwise it will converted to 0 by the model) for the ESS can be used to avoid pumping with avoided curtailment (at no cost) and afterwards being discharged as spillage.

Must-run non-renewable units are always committed, i.e., their commitment decision is equal to 1. All must-run units are forced to produce at least their minimum output.

EFOR is used to reduce the maximum and minimum power of the unit. For hydropower plants it can be used to reduce their maximum power by the water head effect. It does not reduce the maximum charge.

Those generators or ESS with fixed cost >0 are considered candidate and can be installed or not.

Maximum, minimum, and initial storage values are considered proportional to the invested capacity for the candidate ESS units if StorageInvestment is activated.

A generator can belong to several mutually exclusive sets, their names must be separated by "|" when inputted. So if Generator1 belongs to Set1 and Set2, the data entry should be "Set1|Set2". If any of the generators in a group is an installation candidate it is assumed that the exclusivity is yearly, so only one of the generators can be committed in the whole Period. When all mutually exclusive generators in a set are already installed and functioning it is assumed that the exclusivity is hourly and which generator is committed can change every LoadLevel.

If lower and upper bounds of investment/retirement decisions are very close (with a difference <1e-3) to 0 or 1 are converted into 0 and 1.

2.17 Variable maximum and minimum generation

A description of the data included in the files `oT_Data_VariableMaxGeneration.csv` and `oT_Data_VariableMinGeneration.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Generator	Maximum (minimum) power generation of the unit by load level	MW

Not all the generators must be defined as columns of these files, only those with values different from 0.

This information can be used for considering scheduled outages or weather-dependent operating capacity.

To force a generator to produce 0 a lower value (e.g., 0.1 MW) strictly >0, but not 0 (in which case the value will be ignored), must be introduced. This is needed to limit the solar production at night, for example. It can be used also for upper-bounding and/or lower-bounding the output of any generator (e.g., run-of-the-river hydro, wind). If the user introduces a minimum generation value that is greater than the maximum generation value, the model will adjust the minimum generation value to match the maximum.

Internally, all the values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

2.18 Variable maximum and minimum consumption

A description of the data included in the files `oT_Data_VariableMaxConsumption.csv` and `oT_Data_VariableMinConsumption.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Generator	Maximum (minimum) power consumption of the unit by load level	MW

Not all the generators must be defined as columns of these files, only those with values different from 0.

To force a ESS to consume 0 a lower value (e.g., 0.1 MW) strictly >0, but not 0 (in which case the value will be ignored), must be introduced. It can be used also for upper-bounding and/or lower-bounding the consumption of any ESS (e.g., pumped-hydro storage, battery). If the user introduces a maximum consumption value that is lower than the minimum consumption value, the model will adjust the minimum consumption value to match the maximum.

Internally, all the values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

2.19 Variable fuel cost

A description of the data included in the file `oT_Data_VariableFuelCost.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Generator	Variable fuel cost	€/Gcal

Not all the generators must be defined as columns of these files, only those with values different from 0.

Internally, all the values below 1e-4 will be converted into 0 by the model.

Fuel cost affects the linear and constant terms of the heat rate, expressed in Gcal/MWh and Gcal/h respectively.

2.20 Variable emission cost

A description of the data included in the file `oT_Data_VariableEmissionCost.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Generator	Variable emission cost	€/tCO2

Not all the generators must be defined as columns of these files, only those with values different from 0.

Internally, all the values below 1e-4 will be converted into 0 by the model.

2.21 Energy inflows

A description of the data included in the file `oT_Data_EnergyInflows.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Generator	Energy inflows by load level	MWh/h

Not all the generators must be defined as columns of these files, only those with values different from 0.

If you have daily energy inflows data just input the daily amount at the first hour of every day if the ESS have daily or weekly storage capacity.

Internally, all the values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

Energy inflows are considered proportional to the invested capacity for the candidate ESS units if StorageInvestment is activated.

2.22 Energy outflows

A description of the data included in the file `oT_Data_EnergyOutflows.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Generator	Energy outflows by load level	MWh/h

Not all the generators must be defined as columns of these files, only those with values different from 0.

These energy outflows can be used to represent the electric energy extracted from an ESS to produce H2 from electrolyzers, to move EVs, to produce heat, or as hydro outflows for irrigation. The use of these outflows is incompatible with the charge of the ESS within the same time step (as the discharge of a battery is incompatible with the charge in the same hour).

If you have hourly/daily/weekly/monthly/yearly outflows data, you can just input the hourly/daily/weekly/monthly/yearly amount at the first hour of every day/week/month/year.

Internally, all the values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

2.23 Variable maximum and minimum storage

A description of the data included in the files `oT_Data_VariableMaxStorage.csv` and `oT_Data_VariableMinStorage.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Generator	Maximum (minimum) storage of the ESS by load level	GWh

Not all the generators must be defined as columns of these files, only those with values different from 0.

It can be used also for upper-bounding and/or lower-bounding the storage of any generator (e.g., storage hydro). If the user introduces a maximum storage value that is lower than the minimum storage value, the model will adjust the minimum storage value to match the maximum.

For example, these data can be used for defining the operating guide (rule) curves for the ESS.

2.24 Variable maximum and minimum energy

A description of the data included in the files `oT_Data_VariableMaxEnergy.csv` and `oT_Data_VariableMinEnergy.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Generator	Maximum (minimum) power of the unit by load level	MW

Not all the generators must be defined as columns of these files, only those with values different from 0.

It can be used also for upper-bounding and/or lower-bounding the energy of any generator (e.g., storage hydro). If the user introduces a maximum power value that is lower than the minimum power value, the model will adjust the minimum power value to match the maximum.

For example, these data can be used for defining the minimum and/or maximum energy to be produced on a hourly/daily/weekly/monthly/yearly basis (depending on the EnergyType).

2.25 Electricity transmission network

At least one electric transmission line connecting two different nodes must be defined.

A description of the circuit (initial node, final node, circuit) data included in the file `oT_Data_Network.csv` follows:

Header	Description	
LineType	Line type {AC, DC, Transformer, Converter}	
Switching	The transmission line is able to switch on/off	Yes/No
InitialPeriod	Initial period (year) when the unit is installed or can be installed, if candidate	Year
FinalPeriod	Final period (year) when the unit is installed or can be installed, if candidate	Year
Voltage	Line voltage (e.g., 400, 220 kV, 220/400 kV if transformer). Used only for plotting purposes	kV
Length	Line length (only used for reporting purposes). If not defined, computed as 1.1 times the geographical distance	km
LossFactor	Transmission losses equal to the line power flow times this factor	p.u.
Resistance	Resistance (not used in this version)	p.u.
Reactance	Reactance. Lines must have a reactance different from 0 to be considered	p.u.
Susceptance	Susceptance (not used in this version)	p.u.
AngMax	Maximum angle difference (not used in this version)	º
AngMin	Minimum angle difference (not used in this version)	º
Tap	Tap changer (not used in this version)	p.u.
Converter	Converter station (not used in this version)	Yes/No
TTC	Total transfer capacity (maximum permissible thermal load) in forward direction. Static line rating	MW
TTCBck	Total transfer capacity (maximum permissible thermal load) in backward direction. Static line rating	MW
SecurityFactor	Security factor to consider approximately N-1 contingencies. NTC = TTC x SecurityFactor	p.u.
FixedInvestmentCost	Overnight investment (capital -CAPEX- and fixed O&M -FOM-) cost	M€
FixedChargeRate	Fixed-charge rate to annualize the overnight investment cost	p.u.
BinaryInvestment	Binary line/circuit investment decision	Yes/No
InvestmentLo	Lower bound of investment decision	p.u.
InvestmentUp	Upper bound of investment decision	p.u.
SwOnTime	Minimum switch-on time	h
SwOffTime	Minimum switch-off time	h

Initial and final node are the nodes where the transmission line starts and ends, respectively. They must be different.

Depending on the voltage lines are plotted with different colors (orange < 200 kV, 200 < green < 350 kV, 350 < red < 500 kV, 500 < orange < 700 kV, blue > 700 kV).

If there is no data for TTCBck, i.e., TTCBck is left empty or is equal to 0, it is substituted by the TTC in the code. Internally, all the TTC and TTCBck values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

Reactance can take a negative value as a result of the approximation of three-winding transformers. No Kirchhoff's second law disjunctive constraint is formulated for a circuit with negative reactance.

Those lines with fixed cost >0 are considered candidate and can be installed or not.

If lower and upper bounds of investment decisions are very close (with a difference <1e-3) to 0 or 1 are converted into

0 and 1.

2.26 Variable electric transmission line TTC forward and backward (optional files)

A description of the data included in the files `oT_Data_VariableTTCFrw.csv` and `oT_Data_VariableTTCBck.csv` follows:

Identifiers			Header			Description	
Period	Scenario	LoadLev	Initial node	Final node	Circuit	Maximum TTC forward (backward) of an electric transmission line by load level	MW

Not all the electric transmission lines must be defined as columns of these files, only those with values different from 0.

This information can be used for considering weather-dependent maximum capacity of the transmission line.

To force the flow of a transmission line to be 0 a lower value (e.g., 0.1 MW) strictly >0, but not 0 (in which case the value will be ignored), must be introduced. If the user introduces a minimum transmission line capacity value that is greater than the maximum transmission line capacity value, the model will adjust the minimum transmission line capacity value to match the maximum.

If you want to force the flow of a transmission line to be equal to a value, introduce the same value (with opposite sign) in both files (e.g., 125 MW in `oT_Data_VariableTTCFrw.csv` and -125 MW in `oT_Data_VariableTTCBck.csv`) or viceversa.

Internally, all the values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

2.27 Node location

At least two different nodes must be defined.

A description of the data included in the file `oT_Data_NodeLocation.csv` follows:

Identifier	Header	Description	
Node	Latitude	Node latitude	º
Node	Longitude	Node longitude	º

CHAPTER

THREE

HYDROPOWER SYSTEM INPUT DATA

These input files are specifically introduced for allowing a representation of the hydropower system based on volume and water inflow data considering the water stream topology (hydro cascade basins). If they are not available, the model runs with an energy-based representation of the hydropower system.

3.1 Dictionaries. Sets

The dictionaries include all the possible elements of the corresponding sets included in the optimization problem. **You can't use non-English characters (e.g., ó, º)**

File	Description
`oT_Dict_Reservoir.csv`	Reservoirs

The information contained in these input files determines the topology of the hydro basins and how water flows along the different hydropower and pumped-hydro power plants and reservoirs. These relations follow the water downstream direction.

File	Dictionary	Description
`oT_Dict_ReservoirToHydr csv`	ReservoirToHydro	Reservoir upstream of hydropower plant (i.e., hydro takes the water from the reservoir)
`oT_Dict_HydroToReservoi csv`	HydroToReservoir	Hydropower plant upstream of reservoir (i.e., hydro releases the water to the reservoir)
`oT_Dict_ReservoirToPump csv`	ReservoirToPumpedHydro	Reservoir upstream of pumped-hydro power plant (i.e., pumped-hydro pumps from the reservoir)
`oT_Dict_PumpedHydroToRe csv`	PumpedHydroToReservoir	Pumped-hydro power plant upstream of reservoir (i.e., pumped-hydro pumps to the reservoir)
`oT_Dict_ReservoirToRese csv`	ReservoirToReservoir	Reservoir upstream of reservoir (i.e., reservoir one spills the water to reservoir two)

3.2 Natural water inflows

A description of the data included in the file `oT_Data_HydroInflows.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Reservoir	Natural water inflows by load level	m^3/s

All the reservoirs must be defined as columns of these files.

If you have daily natural water inflows data just input the daily amount at the first hour of every day if the reservoir have daily or weekly storage capacity.

Internally, all the values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

3.3 Natural water outflows

A description of the data included in the file `oT_Data_HydroOutflows.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Reservoir	Water outflows by load level (e.g., for irrigation	m^3/s

All the reservoirs must be defined as columns of these files.

These water outflows can be used to represent the water outflows for irrigation.

If you have hourly/daily/weekly/monthly/yearly water outflows data, you can just input the daily/weekly/monthly/yearly amount at the first hour of every day/week/month/year.

Internally, all the values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

3.4 Reservoir

A description of the data included in the file `oT_Data_Reservoir.csv` follows:

Header	Description	
StorageType	Reservoir storage type based on reservoir storage capacity (hourly, daily, weekly, monthly, yearly)	Hourly/Daily/Weekly/Monthly/Yearly
OutflowsType	Water outflows type based on the water extracted from the reservoir (daily, weekly, monthly, yearly)	Daily/Weekly/Monthly/Yearly
InitialStorage	Initial volume stored at the first instant of the time scope	hm^3
Maximum-Storage	Maximum volume that can be stored by the hydro reservoir	hm^3
Minimum-Storage	Minimum volume that can be stored by the hydro reservoir	hm^3
BinaryInvest-ment	Binary reservoir investment decision	Yes/No
FixedInvest-mentCost	Overnight investment (capital -CAPEX- and fixed O&M -FOM-) cost	M€
FixedCharg-eRate	Fixed-charge rate to annualize the overnight investment cost	p.u.
InitialPeriod	Initial period (year) when the unit is installed or can be installed, if candidate	Year
FinalPeriod	Final period (year) when the unit is installed or can be installed, if candidate	Year

The model allways considers a month of 672 hours, i.e., 4 weeks, not calendar months. The model considers a year of 8736 hours, i.e., 52 weeks, not calendar years.

Daily *storage type* means the ESS inventory is assessed every time step. For the daily storage type, it is evaluated at the end of every hour; for the weekly storage type, it is assessed at the end of every day; for the monthly storage type, it is evaluated at the end of every week; and yearly storage type is assessed at the end of every month. *Outflows type* represents the interval when the energy extracted from the storage must be satisfied (for daily outflows type at the end of every day, i.e., the energy consumed must equal the sum of outflows for every day). The *storage cycle* is the minimum between the inventory assessment period (defined by the storage type), the outflows period (defined by the outflows type), and the energy period (defined by the energy type) (only if outflows or energy power values have been introduced). It can be one time step, one day, one week, and one month, but it can't exceed the stage duration. For example, if the stage lasts for 168 hours the storage cycle can only be hourly or daily.

The initial reservoir volume is also fixed at the beginning and end of each stage, only if the initial volume lies between the reservoir storage limits. For example, the initial volume is set for the hour 8736 in case of a single stage or for the hours 4368 and 4369 (end of the first stage and beginning of the second stage) in case of two stages, each with 4368 hours.

3.5 Variable maximum and minimum reservoir volume

A description of the data included in the files `oT_Data_VariableMaxVolume.csv` and `oT_Data_VariableMinVolume.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Reservoir	Maximum (minimum) reservoir volume by load level	hm^3

Not all the reservoirs must be defined as columns of these files, only those with values different from 0.

It can be used also for upper-bounding and/or lower-bounding the volume of any reservoir. If the user introduces a maximum volume value that is lower than the minimum volume value, the model will adjust the minimum volume value to match the maximum.

For example, these data can be used for defining the operating guide (rule) curves for the hydro reservoirs.

CHAPTER

FOUR

HYDROGEN SYSTEM INPUT DATA

These input files are specifically introduced for allowing a representation of the hydrogen energy vector to supply hydrogen demand produced with electricity or by any other means through the hydrogen network. If the hydrogen is only produced from electricity and there is not hydrogen transfer among nodes the hydrogen demand can be represented by the energy outflows associated to the unit (i.e., electrolyzer).

File	Description
`oT_Data_DemandHydrogen.csv`	Hydrogen demand
`oT_Data_NetworkHydrogen.csv`	Hydrogen pipeline network data

4.1 Hydrogen demand

A description of the data included in the file `oT_Data_DemandHydrogen.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Node	Hydrogen demand of the node for each load level	tH2/h

Internally, all the values below if positive demand (or above if negative demand) 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

4.2 Hydrogen transmission pipeline network

A description of the circuit (initial node, final node, circuit) data included in the file `oT_Data_NetworkHydrogen.csv` follows:

Header	Description	
InitialPeriod	Initial period (year) when the unit is installed or can be installed, if candidate	Year
FinalPeriod	Final period (year) when the unit is installed or can be installed, if candidate	Year
Length	Pipeline length (only used for reporting purposes). If not defined, computed as 1.1 times the geographical distance	km
TTC	Total transfer capacity (maximum permissible hydrogen flow) in forward direction. Static pipeline rating	tH2
TTCBck	Total transfer capacity (maximum permissible hydrogen flow) in backward direction. Static pipeline rating	tH2
SecurityFactor	Security factor to consider approximately N-1 contingencies. NTC = TTC x SecurityFactor	p.u.
FixedInvestmentCost	Overnight investment (capital -CAPEX- and fixed O&M -FOM-) cost	M€
FixedChargeRate	Fixed-charge rate to annualize the overnight investment cost	p.u.
BinaryInvestment	Binary pipeline investment decision	Yes/No
InvestmentLo	Lower bound of investment decision	p.u.
InvestmentUp	Upper bound of investment decision	p.u.

Initial and final node are the nodes where the transmission line starts and ends, respectively. They must be different.

If there is no data for TTCBck, i.e., TTCBck is left empty or is equal to 0, it is substituted by the TTC in the code. Internally, all the TTC and TTCBck values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

Those pipelines with fixed cost >0 are considered candidate and can be installed or not.

If lower and upper bounds of investment decisions are very close (with a difference <1e-3) to 0 or 1 are converted into 0 and 1.

CHAPTER

FIVE

HEAT SYSTEM INPUT DATA

These input files are specifically introduced for allowing a representation of the heat energy vector to supply heat demand produced with electricity or with any fuel through the heat network. If the heat is only produced from electricity and there is not heat transfer among nodes the heat demand can be represented by the energy outflows associated to the unit (i.e., heat pump or electric boiler).

File	Description
`oT_Data_ReserveMarginHeat.csv`	Heat reserve margin
`oT_Data_DemandHeat.csv`	Heat demand
`oT_Data_NetworkHeat.csv`	Heat pipeline network data

5.1 Heat adequacy reserve margin

The adequacy reserve margin for heating is the ratio between the available capacity and the maximum demand. It is modeled as the adequacy reserve margin for electricity, but considering the heat demand and the heat capacity of the units. A description of the data included in the file `oT_Data_ReserveMarginHeat.csv` follows:

Identifiers		Header	Description	
Period	Area	ReserveMargin	Minimum heat adequacy reserve margin for each period and area	p.u.

This parameter is only used for system heating generation expansion, not for the system operation. If no value is introduced for an area, the reserve margin is considered 0.

5.2 Heat demand

A description of the data included in the file `oT_Data_DemandHeat.csv` follows:

Identifiers			Header	Description	
Period	Scenario	LoadLevel	Node	Heat demand of the node for each load level	MW

Internally, all the values below if positive demand (or above if negative demand) 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

5.3 Heat transmission pipeline network

A description of the circuit (initial node, final node, circuit) data included in the file `oT_Data_NetworkHeat.csv` follows:

Header	Description	
InitialPeriod	Initial period (year) when the unit is installed or can be installed, if candidate	Year
FinalPeriod	Final period (year) when the unit is installed or can be installed, if candidate	Year
Length	Pipeline length (only used for reporting purposes). If not defined, computed as 1.1 times the geographical distance	km
TTC	Total transfer capacity (maximum permissible heat flow) in forward direction. Static pipeline rating	MW
TTCBck	Total transfer capacity (maximum permissible heat flow) in backward direction. Static pipeline rating	MW
SecurityFactor	Security factor to consider approximately N-1 contingencies. NTC = TTC x SecurityFactor	p.u.
FixedInvestmentCost	Overnight investment (capital -CAPEX- and fixed O&M -FOM-) cost	M€
FixedChargeRate	Fixed-charge rate to annualize the overnight investment cost	p.u.
BinaryInvestment	Binary pipeline investment decision	Yes/No
InvestmentLo	Lower bound of investment decision	p.u.
InvestmentUp	Upper bound of investment decision	p.u.

Initial and final node are the nodes where the transmission line starts and ends, respectively. They must be different.

If there is no data for TTCBck, i.e., TTCBck is left empty or is equal to 0, it is substituted by the TTC in the code. Internally, all the TTC and TTCBck values below 1e-5 times the maximum system demand of each area will be converted into 0 by the model.

Those pipelines with fixed cost >0 are considered candidate and can be installed or not.

If lower and upper bounds of investment decisions are very close (with a difference <1e-3) to 0 or 1 are converted into 0 and 1.

CHAPTER

SIX

FLOW-BASED MARKET COUPLING METHOD

This input file is specifically introduced for allowing the use of the flow-based market coupling method. If they are not available, the model runs with the DCOPF method.

File	Description
`oT_Data_VariablePTDF.csv`	Power transfer distribution factors (PTDF)

6.1 Variable power transfer distribution factors

A description of the data included in the file `oT_Data_VariablePTDF.csv` follows:

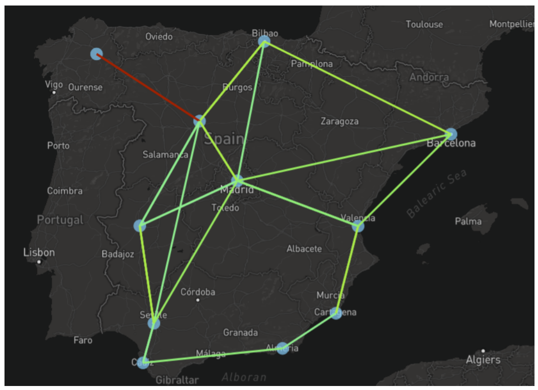
Identifiers			Header				Description	
Period	Scenario	LoadLeve	Initial node	Final node	Circuit	Node	Power transfer distribution factors by load level	p.u.

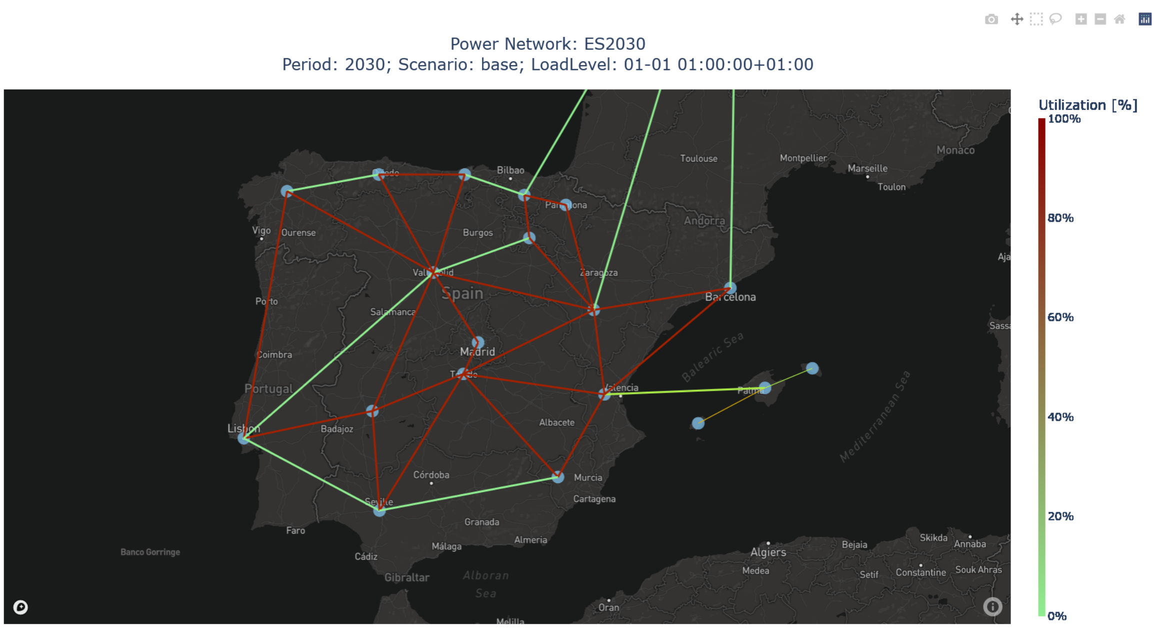
Not all the transmission lines must be defined as columns of these files, only those with values different from 0.

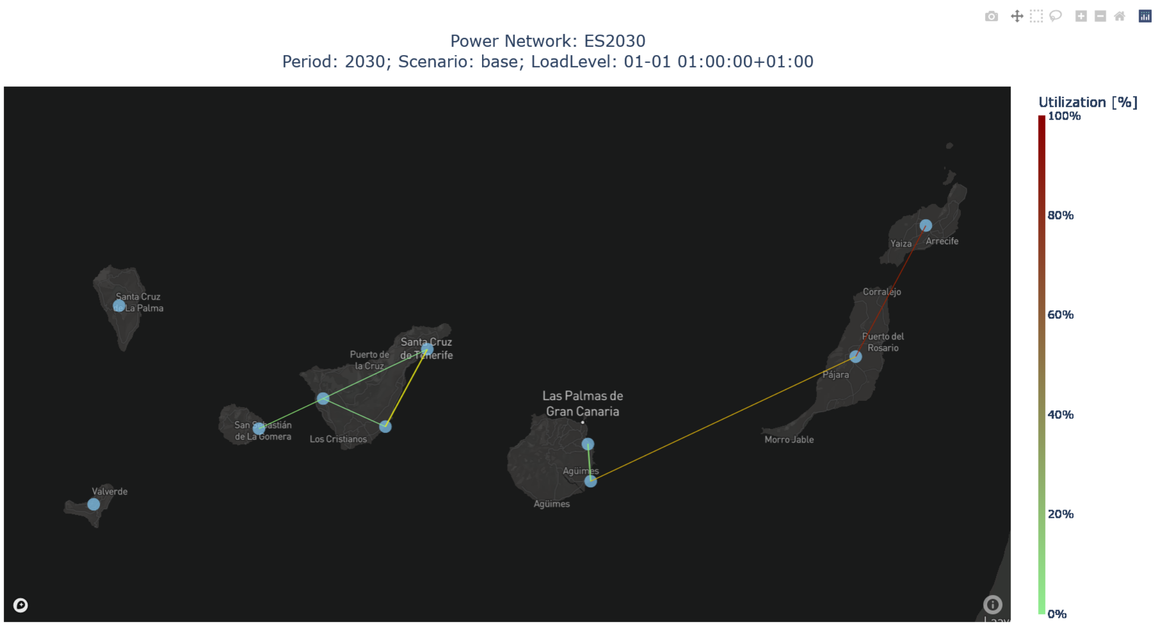
CHAPTER SEVEN

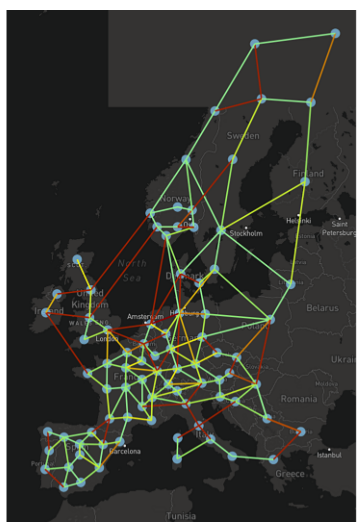
OUTPUT RESULTS

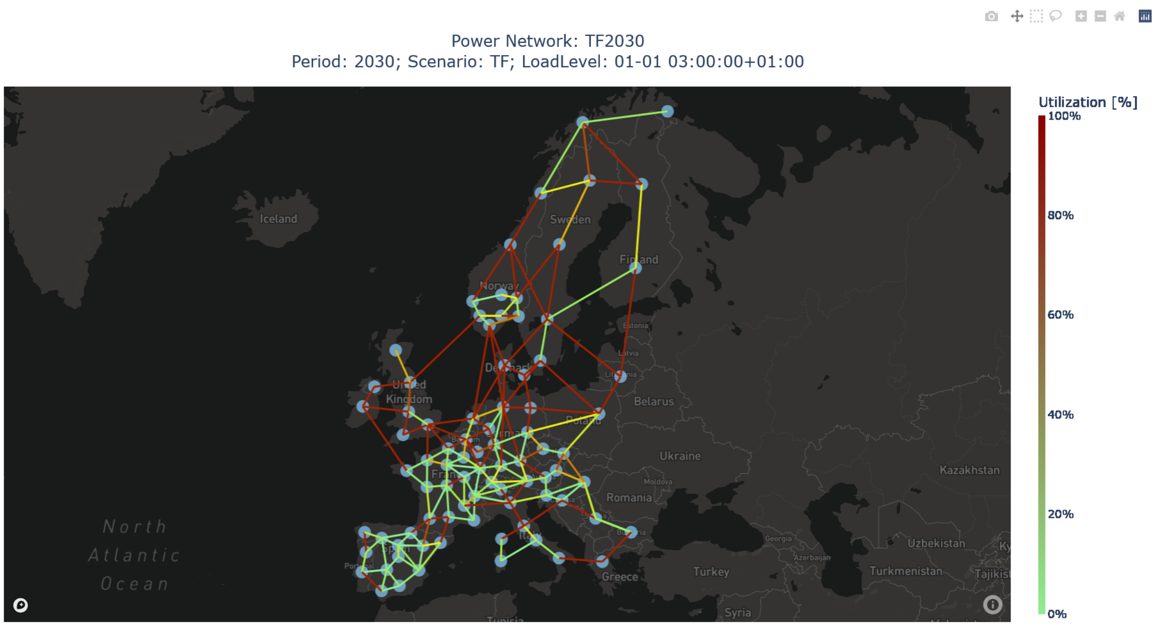
Some maps of the electricity transmission network and the energy share of different technologies is plotted.

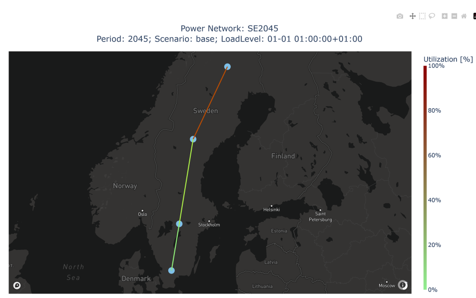


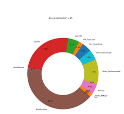


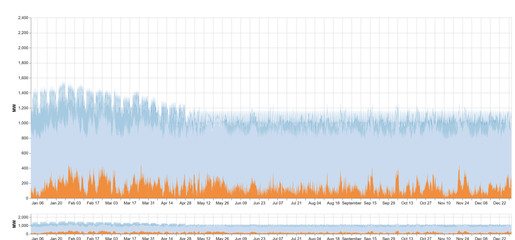

Power Network: ES2030
Period: 2030; Scenario: base; LoadLevel: 01-01 01:00:00+01:00
Utilization [%]
100%
80%
60%
40%
20%
0%
Santa Cruz
La Palma
Santa Cruz
de Tenerife
Puerto de
la Cruz
San Sebastián
de La Gomera
Los Cristianos
Valverde
Las Palmas de
Gran Canaria
Agüimes
Agüimes
Morro Jable
Pájara
Puerto del
Rosario
Corralejo
Yaiza
Arrecife

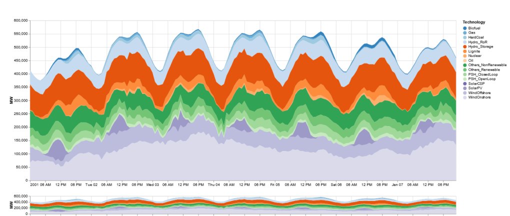

Sweden
Finland
Norway
Stockholm
Helsinki
Saint
Petersburg
North
Sea
United
Kingdom
Ireland
Amsterdam
Belarus
Romania
Barcelona
Istanbul
Greece
Tunisia

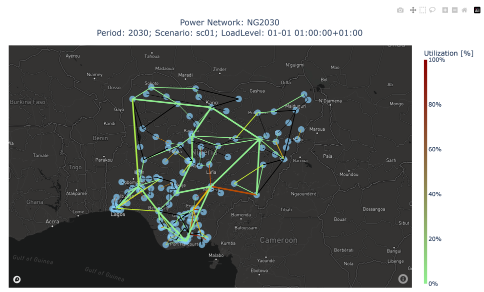

Power Network: TF2030
Period: 2030; Scenario: TF; LoadLevel: 01-01 03:00:00+01:00
Utilization [%]
100%
80%
60%
40%
20%
0%
Iceland
Sweden
Finland
Norway
Estonia
Latvia
Denmark
United Kingdom
Belarus
Ukraine
Kazakhstan
Romania
Uzbekistan
Turkmenistan
Turkey
Greece
Syria
North Atlantic Ocean


Power Network: SE2045
Period: 2045; Scenario: base; LoadLevel: 01-01 01:00:00+01:00
Utilization [%]
100%
80%
60%
40%
20%
0%
Sweden
Finland
Norway
Stockholm
Denmark









Some other additional plots are also plotted by the model. The CSV files used for outputting the results are briefly described in the following items.

The power is expressed in MW, energy or heat in GWh, and costs in M€. Hydrogen is expressed in tH2. Reservoir volume is expressed in hm^3, and water flow in hm^3/s. The energy transported in the electricity network is expressed in GWh-Mkm.

7.1 Investment/Retirement

File `oT_Result_GenerationInvestment.csv`

Identifier	Header	Description
Generator	MW	Generation investment power

File `oT_Result_GenerationInvestmentPerUnit.csv`

Identifier	Header	Description
Generator	MW	Generation investment power

File `oT_Result_GenerationRetirement.csv`

Identifier	Header	Description
Generator	MW	Generation retirement power

File `oT_Result_TechnologyInvestment.csv`

Identifier	Header	Description
Generator	MW	Technology investment power

File `oT_Result_TechnologyInvestmentCost.csv`

Identifier	Header	Description
Generator	M€	Technology investment cost

File `oT_Result_TechnologyInvestmentCostPerMW.csv`

Identifier	Header	Description
Generator	M€/MW	Technology investment cost per MW

File oT_Result_TechnologyRetirement.csv

Identifier	Header	Description
Generator	MW	Technology retirement power

File oT_Result_NetworkInvestment.csv

Identifier			Header	Description
Initial node	Final node	Circuit	p.u.	Electricity network investment decision

File oT_Result_NetworkInvestment_MWkm.csv

Identifier			Header	Description
Initial node	Final node	Circuit	MW-km	Electricity network investment

File oT_Result_ReserveMarginPower.csv

Identifier		Header	Description
Period	Scenario	GW	Reserve margin

File oT_Result_ReserveMarginPerUnit.csv

Identifier		Header	Description
Period	Scenario	p.u.	Per unit reserve margin

File oT_Result_LargestUnitPerUnit.csv

Identifier		Header	Description
Period	Scenario	p.u.	Per unit largest unit

7.2 Electricity generation operation

File oT_Result_GenerationCommitment.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Commitment decision [p.u.]

File oT_Result_GenerationStartUp.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Startup decision [p.u.]

File oT_Result_GenerationShutDown.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Shutdown decision [p.u.]

File oT_Result_GenerationReserveUp.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Upward operating reserve of each generator [MW]

File oT_Result_GenerationReserveDown.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Downward operating reserve of each generator [MW]

File oT_Result_Generation.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Output (discharge in ESS) [MW]

File oT_Result_NetDemand.csv

VRES are the variable renewable energy sources (e.g., wind and solar). Units with null linear variable cost and no storage capacity. The net demand is the demand minus the VRES.

Identifier			Description
Period	Scenario	Load level	Net demand (demand - VRES) [MW]

File oT_Result_NetDemandNetwork.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Electricity net demand (demand - VRES) [MW]

File oT_Result_GenerationSurplus.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Power surplus [MW]

File oT_Result_GenerationRampUpSurplus.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Upward ramp surplus [MW]

File `oT_Result_GenerationRampDwSurplus.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	Downward ramp surplus [MW]

File `oT_Result_GenerationCurtailment.csv`

Identifier			Header	Description
Period	Scenario	Load level	VRES Generator	Curtailed power of VRES [MW]

File `oT_Result_GenerationCurtailmentEnergy.csv`

Identifier			Header	Description
Period	Scenario	Load level	VRES Generator	Curtailed energy of VRES [GWh]

File `oT_Result_GenerationCurtailmentEnergyRelative.csv`

Identifier			Header	Description
Period	Scenario	Load level	VRES Generator	Percentage of energy curtailed of VRES [%]

File `oT_Result_GenerationEnergy.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	Energy (discharge in ESS) [GWh]

File `oT_Result_GenerationEmission.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	CO2 emission [MtCO2]

File `oT_Result_GenerationIncrementalEmission.csv`

Identifier				Header	Description
Period	Scenario	Load level	Area	Generator	Emission rate of the generators with power surplus, except the ESS [tCO2/MWh]

File `oT_Result_TechnologyGeneration.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Output (discharge in ESS) [MW]

File `oT_Result_TechnologyConsumption.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Consumption (charge in ESS) [MW]

File `oT_Result_TechnologyGenerationEnergy.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Energy (discharge in ESS) [GWh]

File `oT_Result_TechnologyGenerationEnergy_AreaName.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Energy (discharge in ESS) per area [GWh]

File `oT_Result_TechnologyCurtailmentEnergy.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Curtailed energy of VRES [GWh]

File `oT_Result_TechnologyCurtailmentEnergyRelative.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Percentage of energy curtailed of VRES [%]

File `oT_Result_TechnologyEmission.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	CO2 emission [MtCO2]

File `oT_Result_TechnologyEmission_AreaName.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	CO2 emission per area [MtCO2]

File `oT_Result_TechnologyOperatingReserveUp.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Upward operating reserve [MW]

File oT_Result_TechnologyOperatingReserveDown.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Downward operating reserve [MW]

File oT_Result_TechnologySpillage.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Spilled energy [GWh]

File oT_Result_TechnologySpillageRelative.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Spilled energy in ESS wrt the energy inflows [%]

7.3 ESS operation

File oT_Result_Consumption.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Consumed/charged power for each ESS [MW]

File oT_Result_ConsumptionEnergy.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Consumed/charged energy for each ESS [GWh]

File oT_Result_ConsumptionReserveUp.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Upward operating reserve of each pump/charge [MW]

File oT_Result_ConsumptionReserveDown.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Downward operating reserve of each pump/charge [MW]

File oT_Result_GenerationConsumptionRatio.csv

Identifier			Heade	Description
Period	Scenario	Load level	Generator	Generation to consumption ratio for each ESS [p.u.] (1 only generating, -1 only consuming, 0 no generating nor consuming, ratio when generating and consuming)

File oT_Result_GenerationOutflows.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Outflows power for each ESS [MW]

File oT_Result_GenerationOutflowsEnergy.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Outflows energy for each ESS [GWh]

File oT_Result_TechnologyConsumption.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Charged power for each ESS [MW]

File oT_Result_TechnologyConsumptionEnergy.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Energy (charge in ESS) [GWh]

File oT_Result_TechnologyConsumptionEnergy_AreaName.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Energy (charge in ESS) per area [GWh]

File oT_Result_TechnologyOutflows.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Outflows power for each ESS [MW]

File oT_Result_TechnologyOutflowsEnergy.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Energy (Outflows in ESS) [GWh]

File oT_Result_TechnologyOperatingReserveUpESS.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Upward operating reserve [MW]

File oT_Result_TechnologyOperatingReserveDownESS.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Downward operating reserve [MW]

File oT_Result_GenerationInventory.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Stored energy (SoC in batteries, reservoir energy in pumped-hydro storage power plants) [GWh]

File oT_Result_GenerationInventoryUtilization.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Utilization factor of the storage (SoC in batteries, reservoir energy in pumped-hydro storage power plants) [p.u.]

File oT_Result_GenerationSpillage.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Spilled energy for each ESS [GWh]

File oT_Result_GenerationSpillageRelative.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Spilled energy for each ESS wrt the energy inflows [%]

File oT_Result_SummaryGeneration.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Generation output (to be used as pivot table)

7.4 Reservoir operation

File oT_Result_ReservoirVolume.csv

Identifier			Header	Description
Period	Scenario	Load level	Reservoir	Reservoir volume [hm^3]

File `oT_Result_ReservoirVolumeUtilization.csv`

Identifier			Header	Description
Period	Scenario	Load level	Reservoir	Utilization factor of the reservoir [p.u.]

File `oT_Result_ReservoirSpillage.csv`

Identifier			Header	Description
Period	Scenario	Load level	Reservoir	Spilled water in reservoir [hm^3]

File `oT_Result_TechnologyReservoirSpillage.csv`

Identifier			Header	Description
Period	Scenario	Load level	Reservoir	Spilled water in reservoir by technology [hm^3]

File `oT_Result_MarginalWaterValue.csv`

Identifier			Header	Description
Period	Scenario	Load level	Reservoir	Water volume value [€/dam^3]

The marginal costs (dual variables) are obtained after fixing the binary investment and operation decisions to their optimal values.

7.5 Electricity balance

File `oT_Result_BalanceEnergy.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Generation, consumption, flows, losses and demand [GWh] (to be used as a pivot table)

File `oT_Result_BalanceEnergyPerArea.csv`

Identifier				Header	Description
Period	Scenario	Load level	Technology	Area	Generation, consumption, flows, losses and demand [GWh]

File `oT_Result_BalanceEnergyPerNode.csv`

Identifier				Header	Description
Period	Scenario	Load level	Technology	Node	Generation, consumption, flows, losses and demand [GWh]

File `oT_Result_BalanceEnergyPerTech.csv`

Identifier					Header	Description
Period	Scenario	Load level	Area	Node	Technology	Generation, consumption, flows, losses and demand [GWh]

7.6 Electricity network operation

File oT_Result_NetworkCommitment.csv

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Line commitment decision [p.u.]

File oT_Result_NetworkSwitchOn.csv

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Line switch on decision [p.u.]

File oT_Result_NetworkSwitchOff.csv

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Line switch off decision [p.u.]

File oT_Result_NetworkFlowElecPerNode.csv

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Electric line flow [MW]

File oT_Result_NetworkEnergyElecPerArea.csv

Identifier			Header		Description
Period	Scenario	Load level	Initial area	Final area	Area flow energy [GWh]

File oT_Result_NetworkEnergyElecTotalPerArea.csv

Identifier		Header		Description
Period	Scenario	Initial area	Final area	Area flow energy [GWh]

File oT_Result_NetworkEnergyElecTransport.csv

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Energy transported [GWh-Mkm]

File oT_Result_NetworkElecUtilization.csv

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Line utilization (i.e., ratio between flow and capacity) [p.u.]

File oT_Result_NetworkLosses.csv

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Line losses [MW]

File oT_Result_NetworkAngle.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Voltage angle [rad]

File oT_Result_NetworkPNS.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Power not served by node [MW]

File oT_Result_NetworkENS.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Energy not served by node [GWh]

File oT_Result_SummaryNetwork.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Network output (to be used as pivot table)

7.7 Hydrogen balance and network operation

File oT_Result_BalanceHydrogen.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Generation, flows, and demand [tH2]

File oT_Result_BalanceHydrogenPerArea.csv

Identifier				Header	Description
Period	Scenario	Load level	Technology	Area	Generation, flows, and demand [tH2]

File oT_Result_BalanceHydrogenPerNode.csv

Identifier				Header	Description
Period	Scenario	Load level	Technology	Node	Generation, flows, and demand [tH2]

File `oT_Result_BalanceHydrogenPerTech.csv`

Identifier					Header	Description
Period	Scenario	Load level	Area	Node	Technology	Generation, flows, and demand [tH2]

File `oT_Result_NetworkFlowH2PerNode.csv`

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Hydrogen pipeline flow [tH2]

File `oT_Result_NetworkHNS.csv`

Identifier			Header	Description
Period	Scenario	Load level	Node	Hydrogen not served by node [tH2]

7.8 Heat generation operation

File `oT_Result_GenerationHeat.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	Output (discharge in ESS) [MW]

File `oT_Result_GenerationSurplusHeat.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	Power surplus [MW]

File `oT_Result_GenerationEnergyHeat.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	Energy (discharge in ESS) [GWh]

File `oT_Result_TechnologyGenerationHeat.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Output (discharge in ESS) [MW]

File `oT_Result_TechnologyGenerationEnergyHeat.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Energy (discharge in ESS) [GWh]

File oT_Result_TechnologyGenerationEnergyHeat_AreaName.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Energy (discharge in ESS) per area [GWh]

7.9 Heat balance and network operation

File oT_Result_BalanceHeat.csv

Identifier			Header	Description
Period	Scenario	Load level	Technology	Generation, flows, and demand [GWh]

File oT_Result_BalanceHeatPerArea.csv

Identifier				Header	Description
Period	Scenario	Load level	Technology	Area	Generation, flows, and demand [GWh]

File oT_Result_BalanceHeatPerNode.csv

Identifier				Header	Description
Period	Scenario	Load level	Technology	Node	Generation, flows, and demand [GWh]

File oT_Result_BalanceHeatPerTech.csv

Identifier					Header	Description
Period	Scenario	Load level	Area	Node	Technology	Generation, flows, and demand [GWh]

File oT_Result_NetworkFlowHeatPerNode.csv

Identifier			Header			Description
Period	Scenario	Load level	Initial node	Final node	Circuit	Heat pipe flow [MW]

File oT_Result_NetworkHTNS.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Heat not served by node [MW]

7.10 Costs and revenues

File `oT_Result_CostSummary.csv`

Identifier	Description
Cost type	Type of cost [M€]

File `oT_Result_CostSummary_AreaName.csv`

Identifier	Header	Description
Cost type	Area	Type of cost per area [M€]

File `oT_Result_CostRecovery.csv`

Identifier	Description
Cost/revenue type	Revenues and investment costs [M€]

File `oT_Result_SummaryKPIs.csv`

Identifier	Description
KPI	Several KPIs

File `oT_Result_TechnologyLCOE.csv`

Identifier	Description
Technology	Levelized Cost of Electricity (LCOE) [€/MWh]

File `oT_Result_TechnologyLCOH.csv`

Identifier	Description
Technology	Levelized Cost of Heating (LCOH) [€/MWh]

File `oT_Result_GenerationCostOandM.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	O&M cost for the generation [M€]

File `oT_Result_GenerationCostOperation.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	Operation cost for the generation [M€]

File `oT_Result_ConsumptionCostOperation.csv`

Identifier			Header	Description
Period	Scenario	Load level	Pump	Operation cost for the consumption [M€]

File oT_Result_GenerationCostOperatingReserve.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Operation reserve cost for the generation [M€]

File oT_Result_ConsumptionCostOperatingReserve.csv

Identifier			Header	Description
Period	Scenario	Load level	Pump	Operation reserve cost for the consumption [M€]

File oT_Result_GenerationCostEmission.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Emission cost for the generation [M€]

File oT_Result_NetworkCostENS.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Reliability cost (cost of the ENS and HNS) [M€]

File oT_Result_RevenueEnergyGeneration.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Operation revenues for the generation [M€]

File oT_Result_RevenueEnergyConsumption.csv

Identifier			Header	Description
Period	Scenario	Load level	ESS Generator	Operation revenues for the consumption/charge [M€]

File oT_Result_RevenueOperatingReserveUp.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Operation revenues from the upward operating reserve [M€]

File oT_Result_RevenueOperatingReserveUpESS.csv

Identifier			Header	Description
Period	Scenario	Load level	ESS Generator	Operation revenues from the upward operating reserve [M€]

File `oT_Result_RevenueOperatingReserveDw.csv`

Identifier			Header	Description
Period	Scenario	Load level	Generator	Operation revenues from the downward operating reserve [M€]

File `oT_Result_RevenueOperatingReserveDwESS.csv`

Identifier			Header	Description
Period	Scenario	Load level	ESS Generator	Operation revenues from the downward operating reserve [M€]

7.11 Marginal information

The marginal costs (dual variables) are obtained after fixing the binary investment and operation decisions to their optimal values.

File `oT_Result_MarginalReserveMargin.csv`

Identifier		Header	Description
Period	Scenario	Area	Marginal of the minimum adequacy electricity system reserve margin [€/MW]

File `oT_Result_MarginalReserveMarginHeat.csv`

Identifier		Header	Description
Period	Scenario	Area	Marginal of the minimum adequacy heat system reserve margin [€/MW]

File `oT_Result_MarginalEmission.csv`

Identifier		Header	Description
Period	Scenario	Area	Marginal of the maximum CO2 emission [€/tCO2]

File `oT_Result_MarginalRESEnergy.csv`

Identifier		Header	Description
Period	Scenario	Area	Marginal of the minimum RES energy [€/MWh]

File `oT_Result_MarginalIncrementalVariableCost.csv`

Identifier				Header	Description
Period	Scenario	Load level	Area	Generator	Variable cost (fuel+O&M+emission) of the generators with power surplus, except the ESS [€/MWh]

File `oT_Result_MarginalIncrementalGenerator.csv`

Identifier				Description
Period	Scenario	Load level	Area	Generator with power surplus, except the ESS, and with the lowest variable cost (fuel+O&M+emission)

File oT_Result_NetworkSRMC.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Locational Short-Run Marginal Cost of electricity [€/MWh], a.k.a. Locational Marginal Price (LMP)

These marginal costs are obtained after fixing the binary and continuous investment decisions and the binary operation decisions to their optimal values. Remember that binary decisions are not affected by marginal changes.

File oT_Result_NetworkSRMCH2.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Locational Short-Run Marginal Cost of H2 [€/kgH2]

These marginal costs are obtained after fixing the binary and continuous investment decisions and the binary operation decisions to their optimal values. Remember that binary decisions are not affected by marginal changes.

File oT_Result_NetworkSRMCHeat.csv

Identifier			Header	Description
Period	Scenario	Load level	Node	Locational Short-Run Marginal Cost of heat [€/MWh]

These marginal costs are obtained after fixing the binary and continuous investment decisions and the binary operation decisions to their optimal values. Remember that binary decisions are not affected by marginal changes.

File oT_Result_MarginalEnergyValue.csv

Identifier			Header	Description
Period	Scenario	Load level	Generator	Energy inflow value [€/MWh]

File oT_Result_MarginalOperatingReserveUp.csv

Identifier			Header	Description
Period	Scenario	Load level	Area	Marginal of the upward operating reserve [€/MW]

File oT_Result_MarginalOperatingReserveDown.csv

Identifier			Header	Description
Period	Scenario	Load level	Area	Marginal of the downward operating reserve [€/MW]

7.12 Operational flexibility

File `oT_Result_FlexibilityDemand.csv`

Identifier			Header	Description
Period	Scenario	Load level	Area	Demand per area variation w.r.t. its mean value [MW]

File `oT_Result_FlexibilityPNS.csv`

Identifier			Header	Description
Period	Scenario	Load level	Area	Power not served per area variation w.r.t. its mean value [MW]

File `oT_Result_FlexibilityNetwork.csv`

Identifier			Header	Description
Period	Scenario	Load level	Area	Exporting flow from each area to other areas variation w.r.t. its mean value [MW]

File `oT_Result_FlexibilityTechnology.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	Technology variation w.r.t. its mean value [MW]

File `oT_Result_FlexibilityTechnologyESS.csv`

Identifier			Header	Description
Period	Scenario	Load level	Technology	ESS Technology variation w.r.t. its mean value [MW]

CHAPTER

EIGHT

MATHEMATICAL FORMULATION

Here we present the mathematical formulation of the optimization problem solved by the **openTEPES** model. See also some TEP-related publications:

- E.F. Álvarez, J.C. López, L. Olmos, A. Ramos "An Optimal Expansion Planning of Power Systems Considering Cycle-Based AC Optimal Power Flow" Sustainable Energy, Grids and Networks, May 2024. 10.1016/j.segan.2024.101413
- E.F. Álvarez, L. Olmos, A. Ramos, K. Antoniadou-Plytaria, D. Steen, and L.A. Tuan "Values and Impacts of Incorporating Local Flexibility Services in Transmission Expansion Planning" Electric Power Systems Research 212, July 2022. 10.1016/j.epsr.2022.108480
- A. Ramos, E. Quispe, S. Lumbreras "OpenTEPES: Open-source Transmission and Generation Expansion Planning" *SoftwareX* 18: June 2022. 10.1016/j.softx.2022.101070
- S. Lumbreras, H. Abdi, A. Ramos, and M. Moradi "Introduction: The Key Role of the Transmission Network" in the book S. Lumbreras, H. Abdi, A. Ramos (eds.) "Transmission Expansion Planning: The Network Challenges of the Energy Transition" Springer, 2020 ISBN 9783030494278 10.1007/978-3-030-49428-5_1
- S. Lumbreras, F. Banez-Chicharro, A. Ramos "Optimal Transmission Expansion Planning in Real-Sized Power Systems with High Renewable Penetration" Electric Power Systems Research 49, 76-88, Aug 2017 10.1016/j.epsr.2017.04.020
- S. Lumbreras, A. Ramos "The new challenges to transmission expansion planning. Survey of recent practice and literature review" Electric Power Systems Research 134: 19-29, May 2016 10.1016/j.epsr.2015.10.013
- Q. Ploussard, L. Olmos and A. Ramos "A search space reduction method for transmission expansion planning using an iterative refinement of the DC Load Flow model" IEEE Transactions on Power Systems 35 (1): 152-162, Jan 2020 10.1109/TPWRS.2019.2930719
- Q. Ploussard, L. Olmos and A. Ramos "An efficient network reduction method for transmission expansion planning using multicut problem and Kron" reduction IEEE Transactions on Power Systems 33 (6): 6120-6130, Nov 2018 10.1109/TPWRS.2018.2842301
- Q. Ploussard, L. Olmos and A. Ramos "An operational state aggregation technique for transmission expansion planning based on line benefits" IEEE Transactions on Power Systems 32 (4): 2744-2755, Oct 2017 10.1109/TPWRS.2016.2614368

8.1 Indices

p	Period (e.g., year)
ω	Scenario
n	Load level (e.g., hour)
g	Generator (thermal or hydro unit or energy storage system)
t	Thermal unit
e	Energy Storage System (ESS)
h	Hydropower or pumped-storage hydro plant (associated to a reservoir modeled in water units)
e', e''	Reservoir (natural water inflows in m^3/s and volume in hm^3)
$h \in up(e')$	Hydro or pumped-storage hydropower plant h upstream of reservoir e'
$h \in dw(e')$	Hydro or pumped-storage hydropower plant h downstream of reservoir e'
$e'' \in up(e')$	Reservoir e'' upstream of reservoir e'
i, j	Node
z	Zone. Each node belongs to a zone $i \in z$
a	Area. Each zone belongs to an area $z \in a$
r	Region. Each area belongs to a region $a \in r$
c	Circuit
ijc	Line (initial node, final node, circuit)
cy	Electricity network cycle
CY	Electricity network cycle basis
CLC	AC candidate electricity transmission lines in a certain cycle
EG, CG	Set of existing and candidate generators
EB, CB	Set of existing and candidate fuel heaters
EE, CE	Set of existing and candidate ESS
ER, CR	Set of existing and candidate reservoirs
EL, CL	Set of existing and non-switchable, and candidate and switchable electric transmission lines
EP, CP	Set of existing and candidate pipelines

8.2 Parameters

They are written in **uppercase** letters.

General		
T	Base period (year)	year
ν	Time step. Duration of the load levels (e.g., 1h, 2 h, 3 h)	
δ	Annual discount rate	p.u.
WG^p	Period (year) weight	p.u.
DF^p	Discount factor for each period (year)	p.u.

Electricity demand		
$D^p_{\omega ni}$	Electricity demand in each node	GW
PD_{pa}	Peak demand in each area	GW
$DUR^p_{\omega n}$	Duration of each load level	h
$CENS$	Cost of energy not served. Value of Lost Load (VoLL)	€/MWh

Hydrogen demand		
$DH^p_{\omega ni}$	Hydrogen demand in each node	tH2
$CHNS$	Cost of hydrogen not served	€/tH2

Heat demand		
$DHt^p_{\omega ni}$	Heat demand in each node	GW
$CHtNS$	Cost of heat not served	€/MWh

Scenarios		
P^p_ω	Probability of each scenario in each period	p.u.

Operating reserves		
URA, DRA	Upward and downward reserve activation	p.u.
$\underline{DtUR}, \overline{DtUR}$	Minimum and maximum ratios downward to upward operating reserves	p.u.
$UR^p_{\omega na}, DR^p_{\omega na}$	Upward and downward operating reserves for each area	GW

Adequacy electricity system reserve margin		
RME_{pa}	Minimum adequacy electricity system reserve margin for each period and area	p.u.

Adequacy heat system reserve margin		
RMH_{pa}	Minimum adequacy heat system reserve margin for each period and area	p.u.

Maximum CO2 emission		
EL_{pa}	Maximum CO2 emission for each period, scenario, and area	MtCO2

Minimum RES energy		
RL_{pa}	Minimum RES energy for each period, scenario, and area	GWh

System inertia		
$SI^p_{\omega na}$	System inertia for each area	s

	Generation system
CFG_g	Annualized fixed cost of a candidate generator
CFR_g	Annualized fixed cost of a candidate generator to be retired
A_g	Availability of each generator for adequacy reserve margin
$\underline{GP}_g, \overline{GP}_g$	Rated minimum load and maximum output of a generator
$\underline{GP}^p_{\omega ng}, \overline{GP}^p_{\omega ng}$	Minimum load and maximum output of a generator
$\underline{GC}^p_{\omega ne}, \overline{GC}^p_{\omega ne}$	Minimum and maximum consumption of an ESS

Table 1 – continued from previous page

$\underline{GH}_g, \overline{GH}_g$	Rated minimum and maximum heat of a CHP or a fuel heater
$CF^p_{\omega ng}, CV^p_{\omega ng}$	Fixed (no load) and variable cost of a generator. Variable cost includes fuel and O&M
CR_g	Operating reserve cost of a generator
$CE^p_{\omega ng}$	Emission cost of a generator
ER_g	Emission rate of a generator
CV_e	Variable cost of an ESS or pumped-storage hydropower plant when charging
RU_g, RD_g	Ramp up/down of a non-renewable unit or maximum discharge/charge rate for ESS discharge/c
TU_t, TD_t	Minimum uptime and downtime of a thermal unit
TS_t	Minimum stable time of a thermal unit
ST_e	Maximum shift time of an ESS unit (in particular, for demand side management)
CSU_g, CSD_g	Startup and shutdown cost of a committed unit
τ_e	Storage cycle of the ESS (e.g., 1, 24, 168, 8736 h -for daily, weekly, monthly, yearly-)
ρ_e	Outflow cycle of the ESS (e.g., 1, 24, 168, 8736 h -for hourly, daily, weekly, monthly, yearly-)
σ_g	Energy cycle of the unit (e.g., 24, 168, 672, 8736 h -for daily, weekly, monthly, yearly-)
GI_g	Generator inertia
EF_e	Round-trip efficiency of the pump/turbine cycle of a pumped-storage hydro plant or charge/disc
PF_h	Production function from water inflows to electricity
PF'_e	Production function from electricity to hydrogen of an electrolyzer
PF''_e	Production function from electricity to heat of a heat pump or an electrical heater
PH''_g	Power to heat ratio for a CHP $\frac{\overline{GP}_g - \underline{GP}_g}{\overline{GH}_g - \underline{GH}_g}$
$\underline{I}^p_{\omega ne}, \overline{I}^p_{\omega ne}$	Minimum and maximum storage of an ESS (e.g., hydropower plant, closed-/open-loop pumped
$I^p_{\omega e}$	Initial storage of an ESS (e.g., hydropower plant, closed-/open-loop pumped-storage hydro)
$\underline{E}^p_{\omega ne}, \overline{E}^p_{\omega ne}$	Minimum and maximum power produced by a unit in an interval defined
$EI^p_{\omega ne}$	Energy inflows of an ESS (e.g., hydropower plant)
$EO^p_{\omega ne}$	Energy outflows of an ESS (e.g., hydrogen, electric vehicle, hydropower plant, demand respons

Hydropower system		
$CFE_{e'}$	Annualized fixed cost of a candidate reservoir	M€/yr
$\underline{I'}^p_{\omega ne'}, \overline{I'}^p_{\omega ne'}$	Minimum and maximum volume of a reservoir	hm^3
$HI^p_{\omega ne'}$	Natural water inflows of a reservoir	m^3/s
$HO^p_{\omega ne'}$	Hydro outflows of a reservoir (e.g., irrigation)	m^3/s

Electricity transmission system		
CFT_{ijc}	Annualized fixed cost of a candidate electricity transmission line	M€/yr
$\overline{F}^p_{\omega nijc}$	Net transfer capacity (total transfer capacity multiplied by the security coefficient) of a transmission line	GW
$\overline{F}'_{ijc}$	Maximum power flow used in the Kirchhoff's 2nd law constraint (e.g., disjunctive constraint for the candidate AC lines)	GW
L_{ijc}	Loss factor of an electric transmission line	p.u.
X_{ijc}	Reactance of an electric transmission line	p.u.
SON_{ijc}, SO	Minimum switch-on and switch-off state of a line	h
S_B	Base power	GW
$'_{cy,i'j'c'}$	Maximum angle used in the cycle Kirchhoff's 2nd law constraint (i.e., disjunctive constraint for a cycle with some AC candidate lines)	rad

The net transfer capacity of an electric transmission line can be different in each direction. However, here it is presented as equal for simplicity.

Hydrogen transmission system		
CFH_{ijc}	Annualized fixed cost of a candidate hydrogen transmission pipeline	M€/yr
$\overline{FH}_{ijc}$	Net transfer capacity (total transfer capacity multiplied by the security coefficient) of a pipeline	tH2

The net transfer capacity of a hydrogen transmission pipeline can be different in each direction. However, here it is presented as equal for simplicity.

Heat transmission system		
CFP_{ijc}	Annualized fixed cost of a candidate heat pipe	M€/yr
$\overline{FP}_{ijc}$	Net transfer capacity (total transfer capacity multiplied by the security coefficient) of a heat pipe	GW

The net transfer capacity of a heat pipe can be different in each direction. However, here it is presented as equal for simplicity.

8.3 Variables

They are written in **lowercase** letters.

Electricity demand		
$ens^p_{\omega ni}$	Energy not served	GW

Hydrogen demand		
$hns^p_{\omega ni}$	Hydrogen not served	tH2

Heat demand		
$htns^p_{\omega ni}$	Heat not served	GW

Generation system		
icg^p_g	Candidate generator or ESS installed or not	{0,1}
rcg^p_g	Candidate generator or ESS retired or not	{0,1}
$gp^p_{\omega ng}, gc^p_{\omega ng}$	Generator output (discharge if an ESS) and consumption (charge if an ESS)	GW
$go^p_{\omega ne}$	Generator outflows of an ESS	GW
$p^p_{\omega ng}$	Generator output of the second block (i.e., above the minimum load)	GW
$c^p_{\omega ne}$	Generator charge	GW
$gh^p_{\omega ng}$	Heat output of a fuel heater	GW
$ur^p_{\omega ng}, dr^p_{\omega ng}$	Upward and downward operating reserves of a non-renewable generating unit	GW
$ur'^p_{\omega ne}, dr'^p_{\omega ne}$	Upward and downward operating reserves of an ESS as a consumption unit	GW
$ei^p_{\omega ne}$	Variable energy inflows of a candidate ESS (e.g., hydropower plant)	GW
$i^p_{\omega ne}$	ESS stored energy (inventory, reservoir energy, state of charge)	GWh
$s^p_{\omega ne}$	ESS spilled energy	GWh
$uc^p_{\omega ng}, su^p_{\omega ng}, sd^p_{\omega ng}$	Commitment, startup, and shutdown of a generation unit per load level	{0,1}
$ucc^p_{\omega ng}$	Consumption commitment of a reversible hydro unit per load level	
$rss^p_{\omega nt}, rsu^p_{\omega nt}, rsd^p_{\omega}$	Stable, ramp up, and ramp down states of a generation unit with minimum stable time per load level	{0,1}
uc'_g	Maximum commitment of a generation unit for all the load levels	{0,1}

Hydropower system		
$icr^p_{e'}$	Candidate reservoir installed or not	{0,1}
$hi^p_{\omega ne'}$	Variable water inflows of a candidate reservoir (e.g., hydropower plant)	m^3/s
$ho^p_{\omega ne'}$	Hydro outflows of a reservoir	m^3/s
$i'^p_{\omega ne'}$	Reservoir volume	hm^3
$s'^p_{\omega ne'}$	Reservoir spilled water	hm^3

Electricity transmission system		
ict^p_{ijc}	Candidate transmission installed or not	{0,1}
$swt^p_{\omega nijc}, son^p_{\omega nijc}, sof^p_{\omega nijc}$	Switching state, switch-on, and switch-off of an transmission electric line	{0,1}
$f^p_{\omega nijc}$	Power flow through an electric transmission line	GW
$l^p_{\omega nijc}$	Half ohmic losses of an electric transmission line	GW
$\theta^p_{\omega ni}$	Voltage angle of a node	rad

Hydrogen transmission system		
ich^p_{ijc}	Candidate hydrogen pipeline installed or not	{0,1}
$fh^p_{\omega nijc}$	Hydrogen flow through a hydrogen pipeline	tH2

Heat transmission system		
icp^p_{ijc}	Candidate heat pipe installed or not	{0,1}
$fp^p_{\omega nijc}$	Heat flow through a heat pipe	GW

8.4 Equations

In this section we replicate the mathematical formulation written in the code, which is specially oriented to numerical stability and efficiency to make easier for the people to understand it. The names between parenthesis correspond to the names of the constraints in the code.

Objective function: minimization of total (investment and operation) cost for the multi-period scope of the model

Electricity, heat, and hydrogen generation, (energy and reservoir) storage and (electricity, hydrogen, and heat) network investment cost plus retirement cost [M€] «`eTotalFCost`» «`eTotalICost`»

$\sum_{p} DF^p[\sum_{g} CFG_g icg^p_g + \sum_{g} CFR_g rcg^p_g + \sum_{e'} CFE_{e'} icr^p_{e'} + \sum_{ijc} CFT_{ijc} ict^p_{ijc} + \sum_{ijc} CFH_{ijc} ich^p_{ijc} + \sum_{ijc} CFP_{ijc} icp^p_{ijc}]+$

Electricity, heat, and hydrogen expected generation operation cost [M€] «`eTotalGCost`»

$\sum_{p\omega ng} DF^p[P^p_\omega DUR^p_{\omega n}(CV^p_{\omega ng} gp^p_{\omega ng} + CF^p_{\omega ng} uc^p_{\omega ng}) + CSU_g su^p_{\omega ng} + CSD_g sd^p_{\omega ng} + CR_g ur^p_{\omega ng} + CR_g dr^p_{\omega ng}]+$

Expected generation emission cost [M€] «`eTotalECost`» «`eTotalECostArea`»

$\sum_{p\omega ng} DF^p P^p_\omega DUR^p_{\omega n} CE^p_{\omega ng} gp^p_{\omega ng}+$

Expected consumption operation cost [M€] «`eTotalCCost`»

$\sum_{p\omega ne} DF^p P^p_\omega DUR^p_{\omega n} CV_e gc^p_{\omega ne}+$

Electricity, hydrogen, and heat expected reliability cost [M€] «`eTotalRCost`»

$\sum_{p\omega ni} DF^p P^p_\omega DUR^p_{\omega n} CENS ens^p_{\omega ni} + \sum_{p\omega ni} DF^p P^p_\omega DUR^p_{\omega n} CHNS hns^p_{\omega ni} + \sum_{p\omega ni} DF^p P^p_\omega DUR^p_{\omega n} CHtNS htns^p_{\omega ni}$

All the periodical (annual) costs of a period p are updated considering that the period (e.g., 2030) is replicated for a number of years defined by its weight WG^p (e.g., 5 times) and discounted to the base year T (e.g., 2020) with this discount factor $DF^p = \frac{(1+\delta)^{WG^p}-1}{\delta(1+\delta)^{WG^p-1+p-T}}$.

Constraints

Generation and network investment and retirement

Investment and retirement decisions in consecutive years «`eConsecutiveGenInvest`» «`eConsecutiveGenRetire`» «`eConsecutiveRsrInvest`» «`eConsecutiveNetInvest`» «`eConsecutiveNetH2Invest`» «`eConsecutiveNetHeatInvest`»

$icg^{p-1}_g \leq icg^p_g \quad \forall pg, g \in CG$

$rcg^{p-1}_g \leq rcg^p_g \quad \forall pg, g \in CG$

$icr^{p-1}_{e'} \leq icr^p_{e'} \quad \forall pe', e' \in CR$

$ict^{p-1}_{ijc} \leq ict^p_{ijc} \quad \forall pijc, ijc \in CL$

$ich^{p-1}_{ijc} \leq ich^p_{ijc} \quad \forall pijc, ijc \in CH$

$icp^{p-1}_{ijc} \leq icp^p_{ijc} \quad \forall pijc, ijc \in CP$

Generation operation

Commitment decision bounded by the investment decision for candidate committed units (all except the VRE units) [p.u.] «`eInstallGenComm`»

$uc^p_{\omega ng} \leq icg^p_g \quad \forall p\omega ng, g \in CG$

Commitment decision bounded by the investment or retirement decision for candidate ESS [p.u.] «`eInstallESSComm`» «`eUninstallGenComm`»

$uc^p_{\omega ne} \leq icg^p_e \quad \forall p\omega ne, e \in CE$

$uc^p_{\omega ne} \leq 1 - rcg^p_e \quad \forall p\omega ne, e \in CE$

Output and consumption bounded by investment or retirement decision for candidate ESS [p.u.] «`eInstallGenCap`» «`eUninstallGenCap`» «`eInstallConESS`»

$\frac{gp^p_{\omega ng}}{GP^p_{\omega ng}} \leq icg^p_g \quad \forall p\omega ng, g \in CG$

$\frac{gp^p_{\omega ng}}{GP^p_{\omega ng}} \leq 1 - rcg^p_g \quad \forall p\omega ng, g \in CG$

$\frac{gc^p_{\omega ne}}{GP^p_{\omega ne}} \leq icg^p_e \quad \forall p\omega ne, e \in CE$

Heat production with fuel heater bounded by investment decision for candidate fuel heater [p.u.] «`eInstallFHUCap`»

$\frac{gh^p_{\omega ng}}{GH^p_{\omega ng}} \leq icg^p_g \quad \forall p\omega ng, g \in CB$

Adequacy electricity system reserve margin [p.u.] «`eAdequacyReserveMarginElec`»

$\sum_{g \in a, EG} \overline{GP}_g A_g + \sum_{g \in a, CG} icg^p_g \overline{GP}_g A_g \geq PD_{pa} RME_{pa} \quad \forall pa$

Adequacy heat system reserve margin [p.u.] «`eAdequacyReserveMarginHeat`»

$\sum_{g \in a, EB} \overline{GH}_g A_g + \sum_{g \in a, CB} icg^p_g \overline{GH}_g A_g \geq PD_{pa} RMH_{pa} \quad \forall pa$

Maximum CO2 emission per period, scenario, and area [MtC02] «`eMaxSystemEmission`»

$\sum_{ng, g \in a} DUR^p_{\omega n} ER_g gp^p_{\omega ng} \leq EL_{pa} \quad \forall p\omega a$

Minimum RES energy per period, scenario, and area [GW] «`eMinSystemRESEnergy`» «`eTotalRESEnergyArea`»

$\frac{\sum_{ng} DUR^p_{\omega n} gp^p_{\omega ng}}{\sum_n DUR^p_{\omega n}} \geq \frac{RL_{pa}}{\sum_n DUR^p_{\omega n}} \quad \forall p\omega a$

Balance of electricity generation and demand at each node with ohmic losses [GW] «`eBalanceElec`»

$\sum_{g \in i} gp^p_{\omega ng} - \sum_{e \in i} gc^p_{\omega ne} + ens^p_{\omega ni} = D^p_{\omega ni} + \sum_{jc} l^p_{\omega nijc} + \sum_{jc} l^p_{\omega njic} + \sum_{jc} f^p_{\omega nijc} - \sum_{jc} f^p_{\omega njic} \quad \forall p\omega ni$

The sum of the inertia of the committed units must satisfy the system inertia for each area [s] «`eSystemInertia`»

$\sum_{g \in a} GI_g uc^p_{\omega ng} \geq SI^p_{\omega na} \quad \forall p\omega na$

Upward and downward operating reserves provided for each area by non-renewable generators (including ESS when generating) and ESS, when charging, [GW] «`eOperReserveUp`» «`eOperReserveDw`»

$\sum_{g \in a} ur^p_{\omega ng} + \sum_{e \in a} ur'^p_{\omega ne} = UR^p_{\omega na} \quad \forall p\omega na$

$\sum_{g \in a} dr^p_{\omega ng} + \sum_{e \in a} dr'^p_{\omega ne} = DR^p_{\omega na} \quad \forall p\omega na$

Ratio between downward and upward operating reserves for each area provided by non-renewable generators (including ESS when generating) and ESS, when charging, [GW] «`eReserveMinRatioDwUp`» «`eReserveMaxRatioDwUp`» «`eRsrvMinRatioDwUpESS`» «`eRsrvMaxRatioDwUpESS`». The corresponding constraints are not formulated if $\underline{DtUR} = 0$ and $\overline{DtUR} = 1$.

$\underline{DtUR}\, ur^p_{\omega ng} \leq dr^p_{\omega ng} \leq \overline{DtUR}\, ur^p_{\omega ng} \quad \forall p\omega ng$

$\underline{DtUR}\, ur'^p_{\omega ne} \leq dr'^p_{\omega ne} \leq \overline{DtUR}\, ur'^p_{\omega ne} \quad \forall p\omega ne$

VRES units (i.e., those with linear variable cost equal to 0 and no storage capacity) do not contribute to the the operating reserves.

Operating reserves from ESS can only be provided if enough energy is available for producing [GW] «`eReserveUpIfEnergy`» «`eReserveDwIfEnergy`»

$ur^p_{\omega ne} \leq \frac{i^p_{\omega ne}}{DUR^p_{\omega n}} \quad \forall p\omega ne$

$dr'^p_{\omega ne} \leq \frac{\overline{I}^p_{\omega ne} - i^p_{\omega ne}}{DUR^p_{\omega n}} \quad \forall p\omega ne$

or for storing [GW] «eESSReserveUpIfEnergy» «eESSReserveDwIfEnergy»

$ur'^p_{\omega ne} \leq \frac{\overline{I}^p_{\omega ne} - i^p_{\omega ne}}{DUR^p_{\omega n}} \quad \forall p\omega ne$

$dr'^p_{\omega ne} \leq \frac{i^p_{\omega ne}}{DUR^p_{\omega n}} \quad \forall p\omega ne$

Maximum and minimum relative inventory of ESS candidates (only for load levels multiple of 1, 24, 168, 8736 h depending on the ESS storage type, represented as $n|\tau_e$) constrained by the ESS commitment decision times the maximum capacity [p.u.] «eMaxInventory2Comm» «eMinInventory2Comm»

$\frac{i^p_{\omega ne}}{\overline{I}^p_{\omega ne}} \leq uc^p_{\omega ne} \quad \forall p\omega ne, n|\tau_e, e \in CE$

$\frac{i^p_{\omega ne}}{\underline{I}^p_{\omega ne}} \geq uc^p_{\omega ne} \quad \forall p\omega ne, n|\tau_e, e \in CE$

Energy inflows of ESS candidates (only for load levels multiple of 1, 24, 168, 8736 h depending on the ESS storage type, represented as $n|\tau_e$) constrained by the ESS commitment decision times the energy inflows data [p.u.] «eInflows2Comm»

$\frac{ei^p_{\omega ne}}{EI^p_{\omega ne}} \leq uc^p_{\omega ne} \quad \forall p\omega ne, n|\tau_e, e \in CE$

ESS energy inventory (only for load levels multiple of 1, 24, 168 h depending on the ESS storage type, represented as $n|\tau_e$) [GWh] «eESSInventory»

$i^p_{\omega,n-\frac{\tau_e}{\nu},e} + \sum_{n'=n-\frac{\tau_e}{\nu}}^{n} DUR^p_{\omega n'}(EI^p_{\omega n'e} - go^p_{\omega n'e} - gp^p_{\omega n'e} + EF_e gc^p_{\omega n'e}) = i^p_{\omega ne} + s^p_{\omega ne} \quad \forall p\omega ne, n|\tau_e, e \in EE$

$i^p_{\omega,n-\frac{\tau_e}{\nu},e} + \sum_{n'=n-\frac{\tau_e}{\nu}}^{n} DUR^p_{\omega n'}(ei^p_{\omega n'e} - go^p_{\omega n'e} - gp^p_{\omega n'e} + EF_e gc^p_{\omega n'e}) = i^p_{\omega ne} + s^p_{\omega ne} \quad \forall p\omega ne, n|\tau_e, e \in CE$

The initial inventory of the ESS candidates divided by its initial storage $I^p_{\omega e}$ is equal to the final reservoir divide by its initial storage [p.u.] «eIniFinInventory».

$\frac{i^p_{\omega,0,e}}{I^p_{\omega e}} = \frac{i^p_{\omega,N,e}}{I^p_{\omega e}} \quad \forall p\omega e, e \in CE$

The initial inventory of the ESS candidates divided by their initial storage $I^p_{\omega e}$ is fixed to the commitment decision [p.u.] «eIniInventory».

$\frac{i^p_{\omega,0,e}}{I^p_{\omega e}} \leq uc^p_{\omega ne} \quad \forall p\omega ne, e \in CE$

Maximum shift time of stored energy [GWh]. It is thought to be applied to demand side management «eMaxShiftTime»

$DUR^p_{\omega n} EF_e gc^p_{\omega ne} \leq \sum_{n'=n}^{n+\frac{ST_e}{\nu}} DUR^p_{\omega n'} gp^p_{\omega n'e} \quad \forall p\omega ne$

ESS outflows (only for load levels multiple of 1, 24, 168, 672, and 8736 h depending on the ESS outflow cycle, represented as $n|\rho_e$) must be satisfied [GWh] «eEnergyOutflows»

$\sum_{n'=n-\frac{\rho_e}{\nu}}^{n} (go^p_{\omega n'e} - EO^p_{\omega n'e}) DUR^p_{\omega n'} = 0 \quad \forall p\omega ne, n|\rho_e$

Maximum and minimum energy production (only for load levels multiple of 24, 168, 672, 8736 h depending on the unit energy type, represented as $n|\sigma_g$) must be satisfied [GWh] «eMaximumEnergy» «eMinimumEnergy»

$\sum_{n'=n-\frac{\sigma_g}{\nu}}^{n} (gp^p_{\omega n'g} - \overline{E}^p_{\omega n'g}) DUR^p_{\omega n'} \leq 0 \quad \forall p\omega ng, n|\sigma_g$

$\sum_{n'=n-\frac{\sigma_g}{\nu}}^{n} (gp^p_{\omega n'g} - \underline{E}^p_{\omega n'g}) DUR^p_{\omega n'} \geq 0 \quad \forall p\omega ng, n|\sigma_g$

Maximum and minimum output of the second block of a committed unit (all except the VRES units) [p.u.] «eMaxOutput2ndBlock» «eMinOutput2ndBlock»

- D.A. Tejada-Arango, S. Lumbreras, P. Sánchez-Martín, and A. Ramos "Which Unit-Commitment Formulation is Best? A Systematic Comparison" IEEE Transactions on Power Systems 35 (4): 2926-2936, Jul 2020 10.1109/TPWRS.2019.2962024

- C. Gentile, G. Morales-España, and A. Ramos "A tight MIP formulation of the unit commitment problem with start-up and shut-down constraints" EURO Journal on Computational Optimization 5 (1), 177-201, Mar 2017. 10.1007/s13675-016-0066-y
- G. Morales-España, A. Ramos, and J. Garcia-Gonzalez "An MIP Formulation for Joint Market-Clearing of Energy and Reserves Based on Ramp Scheduling" IEEE Transactions on Power Systems 29 (1): 476-488, Jan 2014. 10.1109/TPWRS.2013.2259601
- G. Morales-España, J.M. Latorre, and A. Ramos "Tight and Compact MILP Formulation for the Thermal Unit Commitment Problem" IEEE Transactions on Power Systems 28 (4): 4897-4908, Nov 2013. 10.1109/TPWRS.2013.2251373

$\frac{p^p_{\omega ng}+ur^p_{\omega ng}}{\overline{GP}^p_{\omega ng}-\underline{GP}^p_{\omega ng}} \leq uc^p_{\omega ng} - su^p_{\omega ng} - sd^p_{\omega,n+\nu,g} \quad \forall p\omega ng$

$p^p_{\omega ng} - dr^p_{\omega ng} \geq 0 \quad \forall p\omega ng$

Maximum and minimum charge of a non-hydropower ESS [p.u.] «`eMaxCharge`» «`eMinCharge`»

$\frac{c^p_{\omega ne}+dr'^p_{\omega ne}}{\overline{GC}^p_{\omega ne}-\underline{GC}^p_{\omega ne}} \leq 1 \quad \forall p\omega ne$

$c^p_{\omega ne} - ur'^p_{\omega ne} \geq 0 \quad \forall p\omega ne$

Maximum charge of a hydro unit [p.u.] «`eMaxCharge`»

$\frac{c^p_{\omega ne}+dr'^p_{\omega ne}}{\overline{GC}^p_{\omega ne}-\underline{GC}^p_{\omega ne}} \leq ucc^p_{\omega ng} \quad \forall p\omega ne$

Incompatibility between charge and discharge of a non-hydropower ESS [p.u.] «`eChargeDischarge`»

$\frac{p^p_{\omega ne}+URA\, ur^p_{\omega ne}}{\overline{GP}^p_{\omega ne}-\underline{GP}^p_{\omega ne}} + \frac{c^p_{\omega ne}+DRA\, dr'^p_{\omega ne}}{\overline{GC}^p_{\omega ne}-\underline{GC}^p_{\omega ne}} \leq 1 \quad \forall p\omega ne$

Incompatibility between charge and discharge of a hydro unit [p.u.] «`eChargeDischarge`»

$uc^p_{\omega ng} + ucc^p_{\omega ng} \leq 1 \quad \forall p\omega ne$

Total output of a committed unit (all except the VRES units) [GW] «`eTotalOutput`»

$\frac{gp^p_{\omega ng}}{\underline{GP}^p_{\omega ng}} = uc^p_{\omega ng} + \frac{p^p_{\omega ng}+URA\, ur^p_{\omega ng}-DRA\, dr^p_{\omega ng}}{\underline{GP}^p_{\omega ng}} \quad \forall p\omega ng$

Total charge of a non-hydropower ESS [GW] «`eESSTotalCharge`»

$\frac{gc^p_{\omega ne}}{\underline{GC}^p_{\omega ne}} = 1 + \frac{c^p_{\omega ne}-URA\, ur'^p_{\omega ne}+DRA\, dr'^p_{\omega ne}}{\underline{GC}^p_{\omega ne}} \quad \forall p\omega ne$

Total charge of a hydro unit [GW] «`eESSTotalCharge`»

$\frac{gc^p_{\omega ne}}{\underline{GC}^p_{\omega ne}} = ucc^p_{\omega ng} + \frac{c^p_{\omega ne}-URA\, ur'^p_{\omega ne}+DRA\, dr'^p_{\omega ne}}{\underline{GC}^p_{\omega ne}} \quad \forall p\omega ne$

Incompatibility between charge and outflows use of an ESS [p.u.] «`eChargeOutflows`»

$\frac{go^p_{\omega ne}+c^p_{\omega ne}}{\overline{GC}^p_{\omega ne}-\underline{GC}^p_{\omega ne}} \leq 1 \quad \forall p\omega ne$

Logical relation between commitment, startup and shutdown status of a committed unit (all except the VRES units) [p.u.] «`eUCStrShut`»

$uc^p_{\omega ng} - uc^p_{\omega,n-\nu,g} = su^p_{\omega ng} - sd^p_{\omega ng} \quad \forall p\omega ng$

Logical relation between stable, ramp up, and ramp down states (generating units with stable time) [p.u.] «`eStableStates`»

$rss^p_{\omega nt} + rsu^p_{\omega nt} + rsd^p_{\omega nt} = uc^p_{\omega nt} \quad \forall p\omega nt$

Maximum commitment of a committable unit (all except the VRES units) for all the load levels [p.u.] «`eMaxCommitmentYearly`»

$uc^p_{\omega ng} \leq uc'^p_{\omega g} \quad \forall p\omega ng$

Maximum commitment of a committable unit (all except the VRES units) for all the load levels [p.u.] «`eMaxCommitmentHourly`»

$uc^p_{\omega ng} \leq uc'^p_{\omega g} \quad \forall \omega ng$

Maximum of all the capacity factors [p.u.] «`eMaxCommitGenYearly`»

$\frac{gp^p_{\omega ng}}{GP_g} \leq uc'^p_{\omega g} \quad \forall p\omega ng$

Maximum of all the capacity factors [p.u.] «`eMaxCommitGenHourly`»

$\frac{gp^p_{\omega ng}}{GP_g} \leq uc'^p_{\omega g} \quad \forall \omega ng$

Yearly mutually exclusive g and g' units (e.g., thermal, ESS, VRES units) [p.u.] «`eExclusiveGensYearly`»

$uc'^p_{\omega g} + uc'^p_{\omega g'} \leq 1 \quad \forall p\omega gg'$

Hourly mutually exclusive g and g' units (e.g., thermal, ESS, VRES units) [p.u.] «`eExclusiveGensHourly`»

$uc'^p_{\omega g} + uc'^p_{\omega g'} \leq 1 \quad \forall n\omega gg'$

Initial commitment of the units for every period, scenario, and stage is determined by the model based on the merit order loading, including the VRES and ESS units.

Maximum ramp up and ramp down for the second block of a non-renewable (thermal, hydro) unit [p.u.] «`eRampUp`» «`eRampDw`»

- P. Damcı-Kurt, S. Küçükyavuz, D. Rajan, and A. Atamtürk, "A polyhedral study of production ramping," Math. Program., vol. 158, no. 1–2, pp. 175–205, Jul. 2016. 10.1007/s10107-015-0919-9

$\frac{-p^p_{\omega,n-\nu,g} - dr^p_{\omega,n-\nu,g} + p^p_{\omega ng} + ur^p_{\omega ng}}{DUR^p_{\omega n} RU_g} \leq uc^p_{\omega ng} - su^p_{\omega ng} \quad \forall p\omega ng$

$\frac{-p^p_{\omega,n-\nu,g} - ur^p_{\omega,n-\nu,g} + p^p_{\omega ng} + dr^p_{\omega ng}}{DUR^p_{\omega n} RD_g} \geq -uc^p_{\omega,n-\nu,g} + sd^p_{\omega ng} \quad \forall p\omega ng$

Maximum ramp down and ramp up for the charge of an ESS [p.u.] «`eRampUpCharge`» «`eRampDwCharge`»

$\frac{-c^p_{\omega,n-\nu,e} - ur^p_{\omega,n-\nu,e} + c^p_{\omega ne} + dr^p_{\omega ne}}{DUR^p_{\omega n} RD_e} \leq 1 \quad \forall p\omega ne$

$\frac{-c^p_{\omega,n-\nu,e} + dr^p_{\omega,n-\nu,e} + c^p_{\omega ne} - ur^p_{\omega ne}}{DUR^p_{\omega n} RU_e} \geq -1 \quad \forall p\omega ne$

Detection of ramp up and ramp down state for the second block of a non-renewable (thermal) unit with minimum stable time [p.u.] «`eRampUpState`» «`eRampDwState`». The parameter ϵ is added to detect if the generator is ramping up/down. It is defined in the code as 1e-4 (of the ramp up/down limit).

$\frac{-p^p_{\omega,n-\nu,t} + p^p_{\omega nt}}{DUR^p_{\omega n} RU_t} \leq rsu^p_{\omega nt} - \epsilon \cdot rsd^p_{\omega nt} \quad \forall p\omega nt$

$\frac{p^p_{\omega,n-\nu,t} - p^p_{\omega nt}}{DUR^p_{\omega n} RD_t} \leq rsd^p_{\omega nt} - \epsilon \cdot rsu^p_{\omega nt} \quad \forall p\omega nt$

The model can also consider a dead band, which means that ramps below a certain threshold in p.u. set by ϵ should not be restricted. In this case, the ϵ is defined in the code as 1e-2 (of the ramp up/down limit).

$\frac{-p^p_{\omega,n-\nu,t} + p^p_{\omega nt}}{DUR^p_{\omega n} RU_t} \leq rsu^p_{\omega nt} - \epsilon(rsd^p_{\omega nt} - rss^p_{\omega nt}) \quad \forall p\omega nt$

$\frac{p^p_{\omega,n-\nu,t} - p^p_{\omega nt}}{DUR^p_{\omega n} RD_t} \leq rsd^p_{\omega nt} - \epsilon(rsu^p_{\omega nt} - rss^p_{\omega nt}) \quad \forall p\omega nt$

Minimum up time and down time of thermal unit [p.u.] «`eMinUpTime`» «`eMinDownTime`»

- D. Rajan and S. Takriti, "Minimum up/down polytopes of the unit commitment problem with start-up costs," IBM, New York, Technical Report RC23628, 2005. https://pdfs.semanticscholar.org/b886/42e36b414d5929fed48593d0ac46ae3e2070.pdf

$\sum_{n'=n+\nu-TU_t}^{n} su^p_{\omega n't} \leq uc^p_{\omega nt} \quad \forall p\omega nt$

$\sum_{n'=n+\nu-TD_t}^{n} sd^p_{\omega n't} \leq 1 - uc^p_{\omega nt} \quad \forall p\omega nt$

Minimum stable time of a thermal unit [p.u.] «eMinStableTime» In the code you can select a simplified (first) or the tight computational efficient formulation (second).

$rsu^p_{\omega nt} + \sum_{n'=n-TS_t}^{n-\nu} rsd^p_{\omega n't} \leq 1 \quad \forall p\omega nt$

$rsu^p_{\omega nt} + rsd^p_{\omega n't} \leq 1 \quad \forall p\omega nn't, n' \in [n - TS_t, n - \nu]$

Reservoir operation

Maximum and minimum relative volume of reservoir candidates (only for load levels multiple of 1, 24, 168, 8736 h depending on the reservoir volume type, represented as $n|\tau_{e'}$) constrained by the hydro commitment decision times the maximum capacity [p.u.] «eMaxVolume2Comm» «eMinVolume2Comm»

$\frac{i'^p_{\omega ne'}}{\overline{I'}^p_{\omega ne'}} \leq \sum_{h\in dw(e')} uc^p_{\omega nh} \quad \forall p\omega ne', e' \in CR$

$\frac{i'^p_{\omega ne'}}{\underline{I'}^p_{\omega ne'}} \geq \sum_{h\in dw(e')} uc^p_{\omega nh} \quad \forall p\omega ne', e' \in CR$

Operating reserves from a hydropower plant can only be provided if enough energy is available for turbining at the upstream reservoir [GW] «eTrbReserveUpIfEnergy» «eTrbReserveDwIfEnergy»

$ur^p_{\omega nh} \leq \frac{\sum_{e'\in up(h)} i'^p_{\omega ne'}}{DUR^p_{\omega n}} \quad \forall p\omega nh$

$dr^p_{\omega nh} \leq \frac{\sum_{e'\in up(h)} \overline{I'}^p_{\omega ne'} - i'^p_{\omega ne'}}{DUR^p_{\omega n}} \quad \forall p\omega nh$

or for pumping [GW] «ePmpReserveUpIfEnergy» «ePmpReserveDwIfEnergy»

$ur'^p_{\omega nh} \leq \frac{\sum_{e'\in up(h)} \overline{I'}^p_{\omega ne'} - i'^p_{\omega ne'}}{DUR^p_{\omega n}} \quad \forall p\omega nh$

$dr'^p_{\omega nh} \leq \frac{\sum_{e'\in up(h)} i'^p_{\omega ne'}}{DUR^p_{\omega n}} \quad \forall p\omega nh$

Water volume for each hydro reservoir (only for load levels multiple of 1, 24, 168 h depending on the reservoir storage type, represented as $n|\tau_{e'}$) [hm^3] «eHydroInventory»

$i'^p_{\omega,n-\frac{\tau'_e}{\nu},e'} + \sum_{n'=n-\frac{\tau'_e}{\nu}}^{n} DUR^p_{\omega n'}(0.0036 HI^p_{\omega n'e'} - 0.0036 ho^p_{\omega n'e'} - \sum_{h\in dw(e')} gp^p_{\omega n'h}/PF_h + \sum_{h\in up(e')} gp^p_{\omega n'h}/PF_h + + \sum_{h\in up(e')} EF'_e gc^p_{\omega n'h}/PF_h - \sum_{h\in dw(h)} EF'_e gc^p_{\omega n'h}/PF_h) = i'^p_{\omega ne'} + s'^p_{\omega ne'} - \sum_{e''\in up(e')} s'^p_{\omega ne''} \quad \forall p\omega ne', n|\tau_{e'}, e' \in ER$

$i'^p_{\omega,n-\frac{\tau'_e}{\nu},e'} + \sum_{n'=n-\frac{\tau'_e}{\nu}}^{n} DUR^p_{\omega n'}(0.0036 hi^p_{\omega n'e'} - 0.0036 ho^p_{\omega n'e'} - \sum_{h\in dw(e')} gp^p_{\omega n'h}/PF_h + \sum_{h\in up(e')} gp^p_{\omega n'h}/PF_h + + \sum_{h\in up(e')} EF'_e gc^p_{\omega n'h}/PF_h - \sum_{h\in dw(h)} EF'_e gc^p_{\omega n'h}/PF_h) = i'^p_{\omega ne'} + s'^p_{\omega ne'} - \sum_{e''\in up(e')} s'^p_{\omega ne''} \quad \forall p\omega ne', n|\tau_{e'}, e' \in CR$

The initial volume of the hydro reservoir divided by its initial volume $I^p_{\omega e'}$ is equal to the final reservoir divide by its initial volume [p.u.] «eIniFinVolume».

$\frac{i'^p_{\omega,0,e'}}{I^p_{\omega e'}} = \frac{i'^p_{\omega,N,e'}}{I^p_{\omega e'}} \quad \forall p\omega e', e' \in CR$

Hydro outflows (only for load levels multiple of 1, 24, 168, 672, and 8736 h depending on the ESS outflow cycle, represented as $n|\rho_e$) must be satisfied [m^3/s] «eHydroOutflows»

$\sum_{n'=n-\frac{\rho'_e}{\nu}}^{n} (ho^p_{\omega n'e'} - HO^p_{\omega n'e'}) DUR^p_{\omega n'} = 0 \quad \forall p\omega ne', n|\rho'_e$

Electricity network operation

Logical relation between transmission investment and switching {0,1} «eLineStateCand»

$swt^p_{\omega nijc} \leq ict^p_{ijc} \quad \forall p\omega nijc, ijc \in CL$

Logical relation between switching state, switch-on and switch-off status of a line [p.u.] «eSWOnOff»

$swt^p_{\omega nijc} - swt^p_{\omega,n-\nu,ijc} = son^p_{\omega nijc} - sof^p_{\omega nijc} \quad \forall p\omega nijc$

The initial status of the lines is pre-defined as switched on.

Minimum switch-on and switch-off state of a line [h] «eMinSwOnState» «eMinSwOffState»

$\sum_{n'=n+\nu-SON_{ijc}}^{n} son^p_{\omega n'ijc} \leq swt^p_{\omega nijc} \quad \forall p\omega nijc$

$\sum_{n'=n+\nu-SOF_{ijc}}^{n} sof^p_{\omega n'ijc} \leq 1 - swt^p_{\omega nijc} \quad \forall p\omega nijc$

Power flow limit in transmission lines [p.u.] «eNetCapacity1» «eNetCapacity2»

$-swt^p_{\omega nijc} \leq \frac{f^p_{\omega nijc}}{\overline{F}^p_{\omega nijc}} \leq swt^p_{\omega nijc} \quad \forall p\omega nijc$

DC Optimal power flow for existing and non-switchable, and candidate and switchable AC-type lines (Kirchhoff's second law) [rad] «eKirchhoff2ndLaw1» «eKirchhoff2ndLaw2»

$\frac{f^p_{\omega nijc}}{\overline{F}'_{ijc}} - (\theta^p_{\omega ni} - \theta^p_{\omega nj})\frac{S_B}{X_{ijc}\overline{F}'_{ijc}} = 0 \quad \forall p\omega nijc, ijc \in EL$

$-1 + swt^p_{\omega nijc} \leq \frac{f^p_{\omega nijc}}{\overline{F}'_{ijc}} - (\theta^p_{\omega ni} - \theta^p_{\omega nj})\frac{S_B}{X_{ijc}\overline{F}'_{ijc}} \leq 1 - swt^p_{\omega nijc} \quad \forall p\omega nijc, ijc \in CL$

Half ohmic losses are linearly approximated as a function of the power flow [GW] «eLineLosses1» «eLineLosses2»

$-\frac{L_{ijc}}{2} f^p_{\omega nijc} \leq l^p_{\omega nijc} \geq \frac{L_{ijc}}{2} f^p_{\omega nijc} \quad \forall p\omega nijc$

Cycle constraints for AC existing lines with DC optimal power flow formulation [rad] «eCycleKirchhoff2ndLawCnd1» «eCycleKirchhoff2ndLawCnd2». See the cycle constraints for the AC power flow formulation in the following reference:

- E.F. Álvarez, J.C. López, L. Olmos, A. Ramos "An Optimal Expansion Planning of Power Systems Considering Cycle-Based AC Optimal Power Flow" Sustainable Energy, Grids and Networks, May 2024. 10.1016/j.segan.2024.101413

Kirchhoff's second law is substituted by a cycle power flow formulation for cycles with only AC existing lines [rad]

$\sum_{ijc \in cy} f^p_{\omega nijc} \frac{X_{ijc}}{S_B} = 0 \quad \forall p\omega n, cy, cy \in CY$

and disjunctive constraints for cycles with some AC candidate line [rad]

$-1 + ict_{i'j'c'} \leq \frac{\sum_{ijc \in cy} f^p_{\omega nijc} \frac{X_{ijc}}{S_B}}{\overline{}'_{cy,i'j'c'}} \leq 1 - ict_{i'j'c'} \quad \forall p\omega n, cy, i'j'c', cy \in CY, i'j'c' \in CLC$

Flows in AC existing parallel circuits are inversely proportional to their reactances [GW] «eFlowParallelCandidate1» «eFlowParallelCandidate2»

$f^p_{\omega nijc} = \frac{X_{ijc'}}{X_{ijc}} f^p_{\omega nijc'} \quad \forall p\omega nijcc', ijc \in EL, ijc' \in EL$

and disjunctive constraints in AC candidate parallel circuits are inversely proportional to their reactances [p.u.]

$-1 + ict_{ijc'} \leq \frac{f^p_{\omega nijc} - \frac{X_{ijc'}}{X_{ijc}} f^p_{\omega nijc'}}{\overline{F}^p_{\omega nijc}} \leq 1 - ict_{ijc'} \quad \forall p\omega nijcc', ijc \in EL, ijc' \in CL$

Given that there are disjunctive constraints, which are only correct with binary AC investment variables, this cycle-based formulation must be used only with binary AC investment decisions.

Hydrogen network operation

Balance of hydrogen generation by electrolyzers, hydrogen consumption from hydrogen heater using it, and demand at each node [tH2] «eBalanceH2». A transport model is used to model the hydrogen network.

$\sum_{e \in i} \frac{DUR^p_{\omega n}}{PF'_e} gc^p_{\omega ne} - \sum_{g \in i} gh^p_{\omega ng} + hns^p_{\omega ni} = DUR^p_{\omega n} DH^p_{\omega ni} + \sum_{jc} fh^p_{\omega nijc} - \sum_{jc} fh^p_{\omega njic} \quad \forall p\omega ni$

Heat network operation

Energy conversion from any energy type to heating [p.u.] («eEnergy2Heat»)

$gh_{ne} = \frac{DUR^p_{\omega n}}{PF''_e} gc_{ne} \quad \forall ne$

Balance of heat generation produced by CHPs and fuel heaters respectively and demand at each node [GW] «eBalanceHeat». A transport model is used to model the heat network.

$\sum_{g\in i} gh^p_{\omega ng} + htns^p_{\omega ni} = DUR^p_{\omega n} DHt^p_{\omega ni} + \sum_{jc} fp^p_{\omega nijc} - \sum_{jc} fp^p_{\omega njic} \quad \forall p\omega ni$

Flow-based market coupling method

It is based on the flow-based approach presented in:

- Huang D. "Dynamic PTDF Implementation in the Market Model" TU Delft, Delft University of Technology. Sep 2011.

The approach is based on the following equations [GW] [p.u.] «eNetPosition», «eFlowBasedCalcu1» and «eFlowBasedCalcu2»:

$f^p_{\omega nijc} = \sum_{i'} PTDF_{nijci'} (\sum_{g\in i'} gp^p_{\omega ng} - \sum_{e\in i'} gc^p_{\omega ne} + ens^p_{\omega ni'} - D^p_{\omega ni'}) \quad \forall p\omega n, ijc, i', ijc' \in EL$

$-1 + ict_{ijc'} \leq f^p_{\omega nijc} - \sum_{i'} PTDF_{nijci'} (\sum_{g\in i'} gp^p_{\omega ng} - \sum_{e\in i'} gc^p_{\omega ne} + ens^p_{\omega ni'} - D^p_{\omega ni'}) \leq 1 - ict_{ijc'} \quad \forall p\omega nijcc', i', ijc \in EL, ijc' \in CL$

Bounds on generation and ESS variables [GW]

$0 \leq gp^p_{\omega ng} \leq \overline{GP}^p_{\omega ng} \quad \forall p\omega ng$

$0 \leq go^p_{\omega ne} \leq \max(\overline{GP}^p_{\omega ne}, \overline{GC}^p_{\omega ne}) \quad \forall p\omega ne$

$0 \leq gc^p_{\omega ne} \leq \overline{GC}^p_{\omega ne} \quad \forall p\omega ne$

$\underline{GH}^p_{\omega ng} \leq gh^p_{\omega ng} \leq \overline{GH}^p_{\omega ng} \quad \forall p\omega ng$

$0 \leq ur^p_{\omega ng} \leq \overline{GP}^p_{\omega ng} - \underline{GP}^p_{\omega ng} \quad \forall p\omega ng$

$0 \leq ur'^p_{\omega ne} \leq \overline{GC}^p_{\omega ne} - \underline{GC}^p_{\omega ne} \quad \forall p\omega ne$

$0 \leq dr^p_{\omega ng} \leq \overline{GP}^p_{\omega ng} - \underline{GP}^p_{\omega ng} \quad \forall p\omega ng$

$0 \leq dr'^p_{\omega ne} \leq \overline{GC}^p_{\omega ne} - \underline{GC}^p_{\omega ne} \quad \forall p\omega ne$

$0 \leq p^p_{\omega ng} \leq \overline{GP}^p_{\omega ng} - \underline{GP}^p_{\omega ng} \quad \forall p\omega ng$

$0 \leq c^p_{\omega ne} \leq \overline{GC}^p_{\omega ne} \quad \forall p\omega ne$

$\underline{I}^p_{\omega ne} \leq i^p_{\omega ne} \leq \overline{I}^p_{\omega ne} \quad \forall p\omega ne$

$0 \leq s^p_{\omega ne} \quad \forall p\omega ne$

$0 \leq ens^p_{\omega ni} \leq D^p_{\omega ni} \quad \forall p\omega ni$

Bounds on reservoir variables [m^3/s, hm^3]

$0 \leq ho^p_{\omega ne'} \leq \sum_{h\in dw(e')} \overline{GP}^p_{\omega nh} / PF_h \quad \forall p\omega ne'$

$\underline{I'}^p_{\omega ne'} \leq i'^p_{\omega ne'} \leq \overline{I'}^p_{\omega ne'} \quad \forall p\omega ne'$

$0 \leq s'^p_{\omega ne'} \quad \forall p\omega ne'$

Bounds on electricity network variables [GW]

$0 \leq l^p_{\omega nijc} \leq \frac{L_{ijc}}{2} \overline{F}^p_{\omega nijc} \quad \forall p\omega nijc$

$-\overline{F}_{nijc} \leq f^p_{\omega nijc} \leq \overline{F}^p_{\omega nnijc} \quad \forall p\omega nijc, ijc \in EL$

Voltage angle of the reference node fixed to 0 for each scenario, period, and load level [rad]

$\theta^p_{\omega n,node_{ref}} = 0$

Bounds on hydrogen network variables [tH2]

$-\overline{FH}_{ijc} \leq fh^p_{\omega nijc} \leq \overline{FH}_{ijc} \quad \forall p\omega nijc, ijc \in EP$

Bounds on heat network variables [GW]

$-\overline{FP}_{ijc} \leq fp^p_{\omega nijc} \leq \overline{FP}_{ijc} \quad \forall p\omega nijc, ijc \in EP$

CHAPTER

NINE

RESEARCH PROJECTS

The model has being used in these research projects:

- Analysis of energy scenarios for Spain 2030-2050., developed for **Naturgy Innovahub SLU**. September 2024 - December 2024. P. Linares, J.P. Chaves, A.F. Rodríguez Matas

  It aims to contribute to the design of robust investment strategies for Naturgy in the 2030-2050 horizon, with a case study for Spain.

- Quantifying the techno-economic benefits of distributed storage deployment and demand response., developed for **SAMSO, UNEF, AEPIBAL, PIMEC, OCTOPUS**. September 2024 - January 2025. C. Mateo, J.P. Chaves, A. Ramos, F. Martín, T. Gómez, M. Martínez

  It aims to quantify the value of distributed batteries and demand response in the context of the National Integrated Energy and Climate Plan (PNIEC).

- Application of the ENTSO-e cost-benefit analysis method to Conso II pumped-hydro storage, developed for **Iberdrola**. September 2024. L. Rouco, E. Lobato, A. Ramos, L. Olmos

  It aims to write a report on the application of the ENTSO-e 2024 cost-benefit analysis method to Conso II pumped-hydro storage.

- Application of the ENTSO-e cost-benefit analysis method to Aguayo II pumped-hydro storage 2024, developed for **Repsol**. June 2024 - September 2024. A. Ramos, L. Olmos, L. Rouco, E. Lobato

  It aims to write a report on the application of the ENTSO-e 2024 cost-benefit analysis method to Aguayo II pumped-hydro storage.

- Electricity Market Modelling, developed for **Repsol**. November 2023 - April 2024. L. Olmos, A. Ramos, S. Gómez Sánchez

  It aims to develop a tool focused on determining the evolution of prices in the Spanish peninsular electricity system electricity market in the 2023 to 2050 horizon.

- Day-ahead market price simulation tool (HESIME), developed for the **Ministry of Science and Innovation/State Research Agency** (MICIN/AEI/10.13039/501100011033) under the program **Public-Private Partnerships** with **NextGenerationEU/PRTR** funds (CPP2022-009809). April 2023 - March 2026. L. Olmos, A. Ramos, S. Gómez Sánchez

  MINISTERIO DE CIENCIA E INNOVACIÓN · Financiado por la Unión Europea NextGenerationEU · Plan de Recuperación, Transformación y Resiliencia · AGENCIA ESTATAL DE INVESTIGACIÓN

- Open Modelling Toolbox for development of long-term pathways for the energy system in Africa (OpenMod4Africa), developed for the **European Union**. July 2023 - June 2026. L. Olmos, S. Lumbreras, A. Ramos, M.A.E. Elabbas

It aims to develop an open toolbox populated with state-of-the-art models for analysing long-term pathways to sustainable, secure and competitive energy systems in Africa. The Toolbox will build on EU projects like openENTRANCE, Plan4RES and FocusAfrica, and will adapt and further develop open models in accordance with the African context and needs. The models are scalable, and can be applied to cities, industries and countries. Furthermore, a main objective for OpenMod4Africa is capacity building among energy models in academia. Four African universities will be actively involved in adapting models and conducting two regional case studies. The additional capacity and the open Toolbox will enable the universities to train new generations of energy modelling experts for the energy industries in Africa. openTEPES is part of the Africa open energy system modelling toolbox, which is a suite of open and linked state-of-the-art open-source energy system models for Africa.

- Highly-efficient and flexible integration of biomass and renewable hydrogen for low-cost combined heat and power generation to the energy system (Bio-FlexGen), developed for the **European Union**. September 2021 - August 2024. J.P. Chaves, A. Ramos, J.F. Gutierrez

  It aims to significantly increase the efficiency, flexibility and cost effectiveness of renewable energy-based combined heat and power plants (CHP), enabling them to play a key role in integrating fluctuating renewable energy into the energy system, and therefore making a significant contribution to the decarbonization of the energy system.

- Analysis of the role of pumped-hydro storage power plants in the Spanish NECP 2030, developed for **Iberdrola**. July 2023 - October 2023. A. Ramos, P. Linares, J.P. Chaves, M. Rivier, T. Gómez

  It aims to evaluate the role pumped-hydro storage power plants in the Spanish NECP 2030.

- Support in the preparation of the application to the call on innovative energy storage systems, developed for **Glide Energy**. June 2023 - October 2023. L. Rouco, A. Ramos, F.M. Echavarren, R. Cossent

  It is aimed at supporting Glide Energy in the preparation of the application to the call of the Spanish Ministry of Ecological Transition (MITECO) on innovative energy storage systems.

- Analysis of the technical and economic benefits of solar thermal generation in the Spanish peninsular system, developed for **ProTermosolar**. March 2023. A. Ramos, L. Sigrist

  It aims to write a presentation on the quantitative analysis of the technical and economic impact of solar thermal in the operation of the Spanish peninsular system.

- Hydro generation advanced systems: modeling, control, and optimized integration to the system (AVANHID), developed for the **Ministry of Science and Innovation/State Research Agency** (MICIN/AEI/10.13039/501100011033) under the program **Public-Private Partnerships** with **NextGenerationEU/PRTR** funds (CPP2021-009114). October 2022 - September 2025. A. Ramos, J.M. Latorre, P. Dueñas, L. Rouco, L. Sigrist, I. Egido, J.D. Gómez Pérez, F. Labora

- Local markets for energy communities: designing efficient markets and assessing the integration from the electricity system perspective (OptiREC), developed for the **Ministry of Science and Innovation/State Research Agency** (MICIN/AEI/10.13039/501100011033) under the program **Strategic projects oriented to the ecological transition and digital transition** with **NextGenerationEU/PRTR** funds (TED2021-131365B-C43). December 2022 - July 2025. A. Ramos, J.P. Chaves, J.M. Latorre, J. García, M. Troncia, S.A. Mansouri, O.M. Valarezo, M. Mohammed

- Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development (DIAMOND), developed for the **European Union**. October 2022 - August 2025. S. Lumbreras, L. Olmos, A. Ramos

  It will update, upgrade, and fully open six IAMs that are emblematic in scientific and policy processes, improving their sectoral and technological detail, spatiotemporal resolution, and geographic granularity. It will further enhance modelling capacity to assess the feasibility and desirability of Paris-compliant mitigation pathways, their interplay with adaptation, circular economy, and other SDGs, their distributional and equity effects, and their resilience to extremes, as well as robust risk management and investment strategies.

- Application of the ENTSO-e cost-benefit analysis method to Aguayo II pumped-hydro storage, developed for **Repsol**. June 2022. A. Ramos, L. Olmos, L. Sigrist

  It aims to write a report on the application of the ENTSO-e cost-benefit analysis method to Aguayo II pumped-hydro storage.

- Application of the ENTSO-e cost-benefit analysis method to Los Guájares pumped-hydro storage, developed for **VM Energía**. May 2022 - June 2022. A. Ramos, L. Olmos, L. Sigrist

  It aims to write a report on the application of the ENTSO-e cost-benefit analysis method to Los Guájares pumped-hydro storage.

- Impact of the electric vehicle in the electricity markets in 2030, developed for **Repsol**. November 2021 - February 2022. A. Ramos, P. Frías, J.P. Chaves, P. Linares, J.J. Valentín

  It aims to analyze the impact on the electricity markets of the mainland Spanish system of the high penetration of electric vehicles in a 2030 scenario.

- European Climate and Energy Modelling Forum (ECEMF), developed for the **European Union**. May 2021 - December 2024. S. Lumbreras, A. Ramos, L. Olmos, C. Mateo, D. Santos Oliveira, M.S. Gómez Pérez

  It aims to provide the knowledge to inform the development of future energy and climate policies at national and European levels. In support of this aim, ECEMF proposes a range of activities to achieve five objectives and meet the four challenges set out in the call text. ECEMF's programme of events and novel IT-based communications channel will enable researchers to identify and co-develop the most pressing policy-relevant research questions with a range of stakeholders to meet ambitious European energy and climate policy goals, in particular the European Green Deal and the transformation to a climate neutral society.

  Electricity flexibility for the future EU power sector.

  A net-zero emissions power sector requires higher levels of electricity flexibility. But what is the most cost-effective way of providing electricity flexibility? When and where is it more cost-effective to invest in transmission grid upgrades or battery storage? To what extent does the implementation of smart charging of electric vehicles lower investment costs?

- Assessment of the storage needs for the Spanish electric system in a horizon 2020-2050 with large share of renewables, developed for the **Instituto para la Diversificación y Ahorro de la Energía (IDAE)**. January 2021 - June 2022. A. Ramos, P. Linares, J.P. Chaves, J. García, S. Wogrin, J.J. Valentín

  It aims to assess, from a technical and economic point of view, the daily, weekly, and seasonal storage needs for the Spanish electricity system in the 2020-2050 horizon.

- FlexEner. New 100% renewable, flexible and robust energy system for the integration of new technologies in generation, networks and demand - Scenarios, developed for **Iberdrola** under **Misiones CDTI 2019** program (MIG-20201002). October 2020 - December 2023. M. Rivier, T. Gómez, A. Sánchez, F. Martín, A. Ramos, J.P. Chaves, S. Gómez Sánchez, L. Herding, T. Freire

  It aims to investigate new technologies and simulation models in the field of renewable generation, storage systems and flexible demand management and operation of the distribution network. A 100% renewable and decarbonised energy mix is sought, effectively integrated into the electrical system of the future in a flexible, efficient and safe way.

- Improving energy system modelling tools and capacity, developed for the **European Commission**. October 2020 - June 2022. S. Lumbreras, A. Ramos, P. Linares, D. Santos, M. Pérez-Bravo, A.F. Rodríguez Matas, J.C. Romero

  It aims to improve the description of the Spanish energy system in model TIMES-SINERGIA, from the technologies considered or a higher time resolution to the detailed modeling of the power sector, such as the inclusion of transmission constraints, with openTEPES.

- MODESC – Platform of innovative models for speeding the energy transition towards a decarbonized economy, developed for the **Ministry of Science and Innovation** under **Retos Colaboración 2019** program (RTC2019-007315-3). September 2020 - December 2023. T. Gómez, M. Rivier, J.P. Chaves, A. Ramos, P. Linares, F. Martín, L. Herding

  It aims to develop of a global platform that integrates innovative energy simulation and impact assessment models that allow speeding the decarbonization of the electricity system including the electrification of the energy demand.

- Open ENergy TRansition ANalyses for a low-carbon Economy (openENTRANCE), developed for the **European Union**. May 2019 - June 2023. L. Olmos, S. Lumbreras, A. Ramos, E. Alvarez

  It aims to develop, use, and disseminate an open, transparent and integrated modelling platform for assessing low-carbon transition pathways in Europe. It is integrated into the open energy system modelling platform, helping model Europe's energy system and in the list of energy models published under open source licenses.

- Analysis of the expansion and operation of the Spanish electricity system for a 2030-2050 time horizon, developed for **Iberdrola**. January 2019 - December 2021. M. Rivier, T. Gómez, A. Sánchez, F. Martín, T. Freire, J.P. Chaves, T. Gerres, S. Huclin, A. Ramos

It aims to evaluate the potential and role that each generation, storage and consumption technology can play in the future mix of the Spanish electricity system.

CHAPTER TEN

PUBLICATIONS

The **openTEPES** model has been used in these publications:

- E.F. Álvarez "Improving Modelling for Optimal Transmission Expansion Planning". PhD Thesis. Universidad Pontificia Comillas. January 2025. Directors: Andrés Ramos, Luis Olmos.
- D. Santos-Oliveira, S. Lumbreras, E.F. Alvarez, A. Ramos, L. Olmos "Model-based energy planning: a methodology to choose and combine models to support policy decisions" International Journal of Electrical Power and Energy Systems, 159, August 2024. 110048 10.1016/j.ijepes.2024.110048
- E.F. Álvarez, J.C. López, L. Olmos, A. Ramos "An Optimal Expansion Planning of Power Systems Considering Cycle-Based AC Optimal Power Flow" Sustainable Energy, Grids and Networks, May 2024. 10.1016/j.segan.2024.101413
- D. Santos-Oliveira, J. Lecarpentier, S. Lumbreras, L. Olmos, A. Ramos, M. Chammas, Th. Brouhard "The impact of EV penetration on the European Power System: the Tradeoffs in Storage" Social Science Research Network. 2024 10.2139/ssrn.4700642
- A. Ramos A, S. Huclin and J.P. Chaves (2023), "Analysis of different flexible technologies in the Spain NECP for 2030". Front. Built Environ. 9:1065998. 10.3389/fbuil.2023.1065998
- A. Ramos, E. Álvarez "Software implementation". *Second World openTEPES Conference*, July 2023. (Presentation_2ndWorld_Sofware)
- A. Ramos, S. Huclin, J.P. Chaves "Analysis of different flexible technologies in the Spain NECP for 2030". *Second World openTEPES Conference*, July 2023. (Presentation_2ndWorld_Spain_NECP_2030)
- E. Álvarez, L. Olmos, A. Ramos, K. Antoniadou-Plytaria, D. Steen, and L.A. Tuan "Values and Impacts of Incorporating Local Flexibility Services in Transmission Expansion Planning". *Second World openTEPES Conference*, July 2023. (Presentation_2ndWorld_DER_TEP)
- D. Oliviera, L. Olmos, A. Ramos, S. Lumbreras "Impact of the different EV charging strategies at European scale". *Second World openTEPES Conference*, July 2023.
- J.D. Gómez-Pérez, A. Ramos "Characterizing the Spanish hydro basins for their use in openTEPES". *Second World openTEPES Conference*, July 2023. (Presentation_2ndWorld_hydro_basins)
- S. Gómez, A. Ramos, M. Rivier, T. Freire "Role of openTEPES in the FlexEner project". *Second World openTEPES Conference*, July 2023. (Presentation_2ndWorld_FlexEner)
- P. Linares, J.P. Chaves, J. García, J.F. Gutiérrez, A. Ramos, J.J. Valentín "How much storage do we need for the energy transition?". *Second World openTEPES Conference*, July 2023. (Presentation_2ndWorld_storage_need)

- A. Ramos "Ayudando en los estudios eléctricos para hacer la transición energética". OptiMad 2023, Mayo 2023. (Presentation_OptiMad)

- J.J. Valentín, J.P. Chaves, P. Linares, A. Ramos "Análisis de las necesidades de almacenamiento eléctrico de España en el horizonte 2030". Papeles de Energía 174, 72-91, Diciembre 2022.
- S. Huclin et al. "Exploring the roles of storage technologies in the Spanish electricity system with high share of renewable energy" *Energy Reports* 8: 4041-4057, November 2022. 10.1016/j.egyr.2022.03.032
- E.F. Alvarez, L. Olmos, A. Ramos, K. Antoniadou-Plytaria, D. Steen, and L.A. Tuan "Values and Impacts of Incorporating Local Flexibility Services in Transmission Expansion Planning" *Electric Power Systems Research* 212, July 2022. 10.1016/j.epsr.2022.108480
- E.F. Alvarez, L. Olmos, A. Ramos, K. Antoniadou-Plytaria, D. Steen, and L.A. Tuan "Values and Impacts of Incorporating Local Flexibility Services in Transmission Expansion Planning - PSCC2024" *PSCC 2022*. Porto, Portugal. June 2022.
- A. Ramos, E. Quispe, S. Lumbreras "OpenTEPES: Open-source Transmission and Generation Expansion Planning" *SoftwareX* 18: June 2022. 10.1016/j.softx.2022.101070
- A. Ramos, S. Huclin, J.P. Chaves "Analysis of different storage technologies in the Spain NECP for 2030" *IEA Wind Task 25 Spring 2022 meeting*. May 2022. (Presentation_2ndWorld_)
- A. Ramos, E. Alvarez "openTEPES" *First openTEPES World Conference*. March 2022. (Presentation_1stWorld_openTEPES)
- A. Ramos "Assessing the operational flexibility provided by energy storage systems. The Spanish system in 2030" *IEA Wind Task 25 Spring 2021 meeting*. April 2021. (Presentation_IEA_Wind)
- A. Ramos, S. Huclin, J.P. Chaves "Which role will play the pumped-storage hydro and the batteries in the future Spanish system: a case study" *IEEE Sustainable Power & Energy Conference iSPEC 2020*. Chengdu, Sichuan (China). November 2020. (Presentation_IEEE_iSPEC)

CHAPTER

ELEVEN

DOWNLOAD & INSTALLATION

The **openTEPES** model has been developed using Python 3.13.2 and Pyomo 6.9.2 and it uses Gurobi 12.0.2 as commercial MIP solver for which a free academic license is available. It uses Pyomo so that it is independent of the preferred solver. You can alternatively use one of the free solvers HiGHS 1.10.0, SCIP 9.2.1, GLPK 5.0, and CBC 2.10.12. List the serial solver interfaces under Pyomo with this call:

```
pyomo help -s
```

Gurobi, HiGHS, SCIP, or GLPK solvers can be installed as a package:

```
conda install -c gurobi      gurobi
pip   install                highspy
conda install -c conda-forge pyscipopt
conda install                glpk
```

The openTEPES model can also be solved with GAMS and a valid GAMS license for a solver. The GAMS language is not included in the openTEPES package and must be installed separately. This option is activated by calling the openTEPES model with the solver name 'gams'.

Besides, it also requires the following packages:

- Pandas for inputting data and outputting results
- psutil for detecting the number of CPUs
- Plotly, Altair, Colour for plotting results and drawing the network map
- NetworkX for representing the DC power flow formulation with cycle constraints

11.1 Cases

Here, you have the input files of:

- a static small case study of 9 nodes,
- a dynamic (multiyear) small case study of 9 nodes with 13 representative weeks per year,
- another one like a small Spanish system,
- a modified RTS24 case study,
- the static Reliability Test System Grid Modernization Lab Consortium (RTS-GMLC),
- a dynamic (multiyear) Reliability Test System Grid Modernization Lab Consortium (RTS-GMLC) with 13 representative weeks per year, and
- a Nigeria 2030 case study.

11.2 Code

The **openTEPES** code is provided under the GNU Affero General Public License:

- the code can't become part of a closed-source commercial software product
- any future changes and improvements to the code remain free and open

Source code can be downloaded from GitHub or installed with pip

This model is a work in progress and will be updated accordingly. If you want to subscribe to the **openTEPES** model updates send an email to andres.ramos@comillas.edu

11.3 Installation

Installation guide.

There are 2 ways to get all required packages under Windows. We recommend using the Python distribution Miniconda. If you don't want to use it or already have an existing Python (version 3.10) installation, you can also download the required packages by yourself.

Miniconda (recommended)

1. Miniconda. Choose the 64-bit installer if possible.
   1. During the installation procedure, keep both checkboxes "modify the PATH" and "register Python" selected! If only higher Python versions are available, you can switch to a specific Python version by typing `conda install python=<version>`
   2. **Remark:** if Anaconda or Miniconda was installed previously, please check that Python is registered in the environment variables.
2. **Packages and Solver**:
   1. Launch a new Anaconda prompt (or terminal in any IDE)
   2. HiGHS is our recommendation if you want a free and open-source solver.
   3. Install openTEPES via pip by `pip install openTEPES`

Continue at *Get Started*.

GitHub Repository (the hard way)

1. Clone the openTEPES repository
2. Launch the Anaconda prompt (or terminal in any IDE)
3. Set up the path by `cd "C:\Users\<username>\...\openTEPES"`. (Note that the path is where the repository was cloned.)
4. Install openTEPES via pip by `pip install .`

Solvers

HiGHS

The HiGHS solver can also be used. It can be installed using: `pip install highspy`. This solver is activated by calling the openTEPES model with the solver name 'appsi_highs'.

Gurobi

Another recommendation is the use of Gurobi solver. However, it is commercial solver but most powerful than open-source solvers for large-scale problems. As a commercial solver it needs a license that is free of charge for academic usage by signing up in Gurobi webpage. You can also ask for an evaluation license for 30 days to test the solver. It can be installed using: `conda install -c gurobi gurobi` and then ask for an academic or commercial license. Activate the license in your computer using the `grbgetkey` command (you need to be in a university internet domain if you are installing an academic license).

GLPK

As an easy option for installation, we have the free and open-source GLPK solver. However, it takes too much time for large-scale problems. It can be installed using: `conda install glpk`.

CBC

The CBC solver is also another free and open-source solver. For Windows users, the effective way to install the CBC solver is downloading the binaries from this site, copy and paste the *cbc.exe* file to the PATH that is the "bin" directory of the Anaconda or Miniconda environment. Under Linux, it can be installed using: `conda install -c conda-forge coincbc`.

Mosek

Another alternative is the Mosek solver. Note that it is a commercial solver and you need a license for it. Mosek is a good alternative to deal with QPs, SOCPs, and SDPs problems. You only need to use `conda install -c mosek mosek` for installation and request a license (academic or commercial). To request the academic one, you can request here. Moreover, Mosek brings a license guide. But if you are request an academic license, you will receive the license by email, and you only need to locate it in the following path `C:\Users\<username>\mosek` in your computer.

GAMS

The openTEPES model can also be solved with GAMS and a valid GAMS license for a solver. The GAMS language is not included in the openTEPES package and must be installed separately. This option is activated by calling the openTEPES model with the solver name 'gams'.

11.4 Get started

Developers

By cloning the openTEPES repository, you can create branches and propose pull-request. Any help will be very appreciated.

Users

If you are not planning on developing, please follows the instructions of the *Installation*.

Once installation is complete, openTEPES can be executed in a test mode by using a command prompt. In the directory of your choice, open and execute the openTEPES_run.py script by using the following on the command prompt (Windows) or Terminal (Linux). (Depending on what your standard python version is, you might need to call *python3* instead of *python*.):

```
openTEPES_Main
```

Then, four parameters (case, dir, solver, results, and console log) will be asked for.

Remark: at this step only press enter for each input and openTEPES will be executed with the default parameters.

After this in a directory of your choice, make a copy of the 9n or sSEP case to create a new case of your choice but using the current format of the CSV files. A proper execution by `openTEPES_Main` can be made by introducing the new case and the directory of your choice. Note that the solver is **glpk** by default, but it can be changed by other solvers that pyomo supports (e.g., gurobi, highs).

Then, the **results** should be written in the folder who is called with the case name. The results contain plots and summary spreadsheets for multiple optimized energy scenarios, periods and load levels as well as the investment decisions.

Note that there is an alternative way to run the model by creating a new script **script.py**, and write the following:

```
from openTEPES.openTEPES import openTEPES_run

openTEPES_run(<dir>, <case>, <solver>, <results>, <log>)
```

Run the Tutorial

It can be run in Binder:

CHAPTER

TWELVE

QUESTIONS & ANSWERS (Q&A)

12.1 How can I install it?

- openTEPES has been tested to be used in Microsoft Windows and Ubuntu (a Linux distribution)
- The installation documentation can be found at

  https://opentepes.readthedocs.io/en/latest/Download.html

  https://pascua.iit.comillas.edu/aramos/openTEPES_installation.pdf
- We recommend using these solvers

  Gurobi because there is a license that is free of charge for academic usage

  HiGHS as a free solver

  GAMS/CPLEX for those institutions having the corresponding licenses

12.2 What PC do I need?

- openTEPES requirements depend on the case study
- The main dimensions to take care of are:

  Time (periods, load levels)

  Network (nodes, lines, transportation or DC power flow, ohmic losses)

  Stochasticity (scenarios)

  Binary investment decisions (generators, storage, transmission lines, etc.), operation decisions (commitment, startup, shutdown, etc.), mutual exclusivity
- As a rule of thumb, a linear optimization problem requires 1 GB of memory for every 1 million rows
- So, depending on the size of the optimization problem and the available memory, you may or may not be able to run it on your PC. As an example, the case studies provided can be run in a laptop with 16 MB of memory.

12.3 First steps

- openTEPES is provided with seven case studies. Each one has varied characteristics
- Check that you can run them on your PC. Some of them may not run if you have a PC with too little memory

12.4 Potential issues

- Check that any item you define (generator, node, technology, area, etc.) is included in the corresponding dictionary (oT_Dict_Generation, oT_Dict_Node, oT_Dict_Technology, oT_Dict_Area, etc.). Otherwise, the optimization problem will not run
- openTEPES is implicitly a network model. Therefore, at least two nodes and one electrical transmission line connecting them must be defined
- At least one generator must be defined. A thermal generator has a larger than zero variable cost (the product of fuel cost times the linear term 0). A variable renewable energy unit has zero variable cost (the product of fuel cost times the linear term = 0)
- Check the correspondence between the resources you define for the system in the case study to be run and the nodes where they are deemed to be located. The location within the grid of any resource defined must be specified.
- Check that all the demand in the system within the case study is located in a node that can be served with the energy output of some resources located in any node that is connected/to be connected to the former, possibly including generation representing energy not served (ENS).

12.5 Some tips

On building an appropriate set of input data files for a case study that can be run on openTEPES:

- How can I strongly reduce the size of the case study for testing purposes

  Delete the duration (column D in oT_Data_Duration) of the load levels you want to ignore. For example, if you delete the duration beyond the first 168 hours, you are considering just the first week of the year in the case study

  Put a time step of 2 or 3 hours in the oT_Data_Parameter file. This will reduce the number of load levels by 2 or 3

  For working with representative stages see, for example, the 9n7y case study
- Relaxing the binary condition of binary variables

  In the oT_Data_Option file you can force or relax the binary condition of the binary variables.

  Besides, in oT_Data_Generation and oT_Data_Network they can also be relaxed individually for each generator or transmission line.
- How to ignore a scenario or a period

  Assign probability 0.0 to the scenario in oT_Data_Scenario or weight 0.0 to the period in oT_Data_Period
- How to ignore a generator

  Don't assign a node to it in oT_Data_Generation, i.e., leave the node column empty

  Set the initial period where the generator can be in operation beyond the year of study in oT_Data_Generation
- How to ignore a line

  Set the initial period where the line can be in operation beyond the year of study in oT_Data_Network
- All the empty cells of the CSV files are substituted internally by openTEPES with 0.0

  Therefore, if you want to set the generation of a solar PV to 0.0 at night, then you must put a small value 0.000001 that will be substituted internally by openTEPES with 0.0. If the cell is left empty openTEPES will consider the rated capacity of the solar PV unit defined in oT_Data_Generation as the generation at night.

- There is no need to include the column for a certain resource within an input data file if there is not data to be defined for this resource within that file. Empty columns don't need to be included in the input data CSV files, including oT_Data_VariableMaxGeneration, oT_Data_VariableMinGeneration, oT_Data_VariableMaxConsumption, oT_Data_VariableMinConsumption, etc.

On analysing output data:

- Make sure the problem solving process has been successfully completed, reaching optimality (console log and solver log file provide information on this).
- If the problem solving process has not produced an optimal solution, check if the system conditions defined within the input data files are too tight, i.e., the system may has not been provided with a large enough amount of flexibility for the model to find the optimal problem solution. If this may be the case, some problem constraints could/should be relaxed to allow the model to compute an optimal solution.
- Check the level of the overall system variables in the output energy balance files (e.g., oT_Result_BalanceEnergyPerArea, oT_Result_BalanceEnergyPerTech) to assess whether they seem to make sense. Focus first on certain specific variables, including the ones that follow:

  Non-served energy amounts

  Amounts of spilled and curtailed energy

  Overall output by technology if you have some reference levels for this to compare to

- Whenever the level of some variables at system level does not seem to be reasonable, check the output data file for the energy balance at area (country) level, to try to locate in which area within the system the problem may be located

CHAPTER

THIRTEEN

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