iDesignRES

Integrated Design of the Components of the Energy System to Plan the Uptake of Renewable Energy Sources:

An Open Source Toolbox

Multi-physics component models

Companion report to Deliverable 1.2 Multi-physics component models

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1. EXECUTIVE SUMMARY

Robust Planning and optimal allocation of resources is at the heart of needed actions required to successfully decarbonise our energy systems. Radical changes are needed to remove the reliance on unabated fossil fuels. A significant increase in the use of intermittent renewable energy sources is expected to be core in reaching the targets. However, when planning how to develop and decarbonise regional energy systems it is important to stress-test that the system can handle the inherent variability in intermittent renewable energy sources. To this end, a set of component models have been developed in the iDesignRES project (WP1). These models and their software features have been made publicly available as the main output of this deliverable. Some of these models will be used in a stand-alone mode, primarily to investigate electricity and gas systems. The other models will be used to analyse the behaviour of the integrated systems with several energy carriers and will be coupled with an assembly tool currently under development in the project (WP2).

This report **accompanies and supplements** the deliverable D1.2 "Multi-physics component models" of the iDesignRES project. The deliverable consists of the set of models and related software provided through the work in WP1. The **deliverable releases these models** as a step forward to their certification and testing, i.e., the next deliverable in WP1: D1.3. This report provides an overview of all the models in terms of purpose, model design philosophy, input and output, implemented features, core assumptions and repository. For comprehensive model documentation we refer the interested readers to each model's repository available at https://github.com/iDesignRES .

2. The iDesignRES multi-physics component modules – an overview

Developing our energy systems towards a higher degree of integration and coupling between the traditional sectors is a natural consequence of the quest for decarbonisation with an additional potential for cost- and energy- savings. Furthermore, decarbonisation efforts are likely to imply a significant increase in reliance on intermittent renewable energy sources across energy carriers and end-use sectors. Energy system planning, both for investments and operations becomes inherently more complex with these developments. Hence, there is a need for tools that can handle the complexity and be used for guidance and to strengthen the decision basis of key actors.

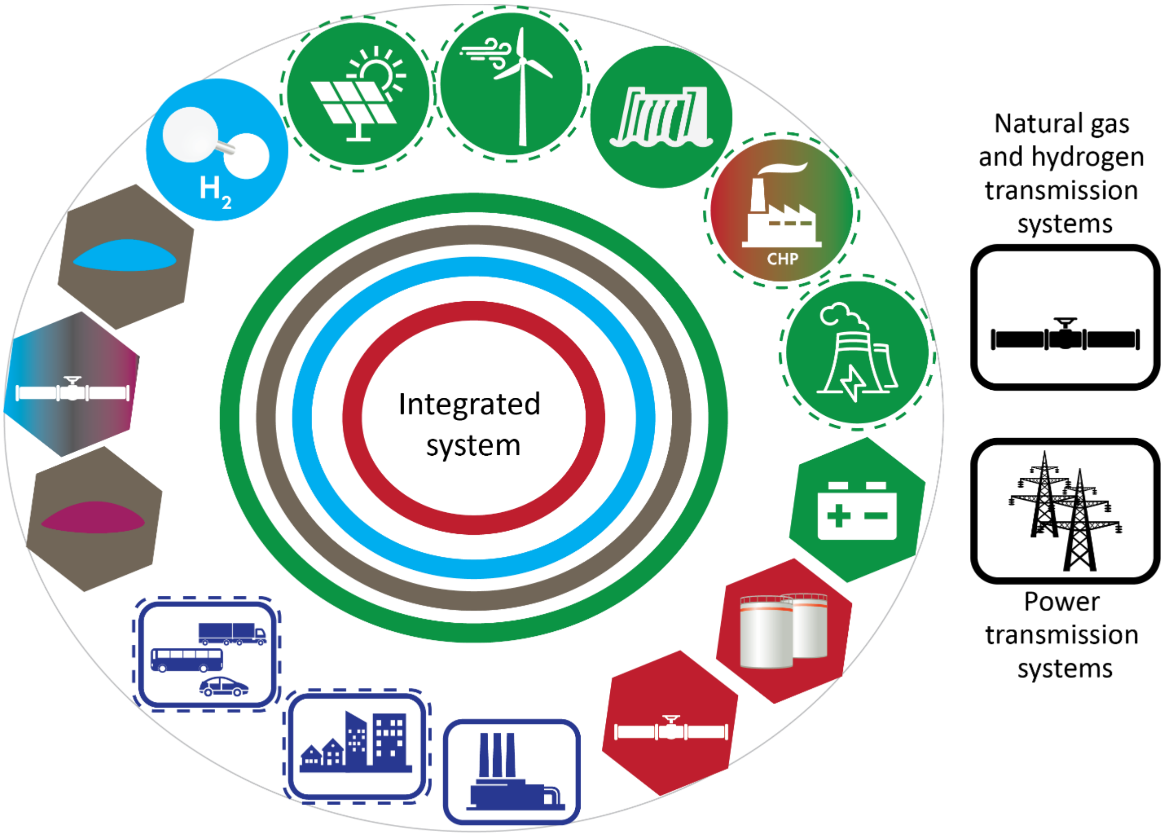


Figure 1 Overview of component models for operational analyses. Note: Integrated system analyses include components for heat (red), hydrogen (light blue), natural gas (grey), electricity (green) and CO_2 (violet).

This companion report provides an overview of multi-parameter component models that have been adapted or derived within WP1 "Multi-Physics component models: Implementation and development". These models constitute D1.2 "Multi-physics component models", and are categorized by their intended use:

- Detailed system models for one energy carrier, e.g. electricity and natural gas. Intended use for detailed analyses of said systems. [Presented in section 3]
- Energy consumer models: Industry, buildings and transport. Detailed models for the energy consumers of a given area/industry type. Modules can be used stand-alone or provide data to be used together with the "Assembling multi-physics modules and components tool" derived in Task 2.2. The assembly tool will be delivered at M18, and will enable operational analyses of integrated, multi-carrier regional energy systems. [Presented in section 4]

- Multi-parameter models that will be directly integration into the assembly tool of Task 2.2. [Presented in section 5]
- Stand-alone component models with detailed operational analysis capabilities. The assembly tool of Task 2.2 will sample data from the component model outputs and use in the assessment of the integrated, multi-carrier energy system operations. [Presented in section 6].

An overview of the prepared models is given in Figure 1. Here, production models are shown as circles, transport and storage models are shown as hexagons and energy consumers as rectangles. Table 1 provides an overview of the delivered component models and their characterisation.

Table 1: WP1 component models and characterization Component category	**Component models provided in this deliverable (Detailed in following chapters)**
Renewable energy sources	Wind and solar resources (integrated into the wind – and solar power modules, respectively) Hydro-potentials- integrated in power system models as well as capacity expansion models
Non-renewable primary energy sources	Mainly input data and sources availability
Non-renewable energy conversion	Hydrogen production through reforming
Non-renewable electricity production	Nuclear power production
Renewable energy conversion	Hydro, wind and solar power production Combined heat and power (CHP)
Energy storage	Batteries, hydrogen and hydro (hydro storage integrated in hydro-power model and power system models)
Transport pipelines	CO_2 and hydrogen pipeline models, natural gas and hydrogen transmission system
Transmission power lines	Power transmission systems
Energy consumers	Buildings, transport, and industry

3. Detailed system models

3.1. Power System setup: Zoomed in NUTS2+ and modelling sequence

Purpose of the model

This does not so much describe a model as rather a sequence of models. The purpose is to analyse and investigate the behaviour of the system at a detailed level; For instance, performing an ACOPF analysis of Spain or some other European Country. Depending on the used model for the detailed analysis, it may be necessary to clip away the target country from the remainder of the system in a reasonable way. This is done by the currently described model sequence.

Model design philosophy

The main idea is to first make a NUTS0 (NUTS1 or finer) computation of the EU system at mid-term or long-term level. This can be done using the Plan4Res / SMS++ computational suite. The computation should be made at a level (e.g., NUTS0) at which one reasonably assumes the data of the various countries to be useful – or "correct". Another feature worth incorporating is evidently the computation ability. This mid-term computational step may be preceded by an investment step to ensure that sufficient generation and transfer capacity are available. The main purpose of the mid-term computation is to ensure that seasonal storage capacity is properly evaluated as this has an important impact on the management of the system.

Input to and output from the model

Key outputs of the above mid-term computation are:

- Cost-2-go functions for the seasonal storages in each of the nodes, where present.
- Power flow between the various nodes
- Overall power balances

The latter information may help detect early issues with the data – for instance if generation with key resources are off by an order of magnitude as compared to what would be reasonable.

The power flows between the various nodes will help "cut out" the target country. This can be done by distributing the flow over the relevant buses connecting the target country to some country Y, to be clipped off. Exports / Imports can then be dispatched as load / generation; The cost-2-go functions can simply be included in the target country, by assuming for instance that what was valued at a larger level is some (weighted) sum of what was done at a finer level. This allows for an immediate dispatch of the cost-2-go functions from larger to smaller by the use of linear algebra.

Implemented features

Options to consider are:

- Whether or not to precede the computation with a run of the investment solver
- The computational mode for seasonal storage – among things how many scenarios.
- The amount of detail to model for the generation assets

3.2. Power transmission systems

Purpose of the model

The SMS++ framework is a modelling system for mathematical optimization problems with structure that can be exploited. It is particularly well suited for very large models. The Plan4Res suite is an instantiation of this framework for Electrical system modelling. It contains an investment module, a seasonal storage valuation module and a unit-commitment module. The particularity of the framework is that it also allows one to embed all these models hierarchically and thus obtain a consistent framework across all time horizons (long term to short term). For the purpose of iDesignRES the subpart related to the network flow equations considered: this would refer specifically to DCNetworkBlock and ACNetworkBlock

Model design philosophy

Since SMS++ is coded in C++, the same holds true for the above given modules. Moreover, since the DC powerflow equations are standard, they are implemented as such. However, if the data showcases that the network does not change over time, the PTDF matrix is computed only once. In case of ill conditioning, it is possible to apply Tikhonov regularization.

The AC equations are also classic and implemented similarly to those in the well-known MATPOWER suite. The bus injection model is thus used.

Input to and output from the model

In order to make use of the given models, one has to append the input data files with the subsequent additional data. All SMS++ / Plan4res input files are essentially netcdf files, but these can be edited and worked with as regular structured text files as well before using a conversion tool such as ncgen (text to netcdf) or ncdump (netcdf to text).

Concerning the DC network / DC OPF computations, one needs to specify the following variable:

- LineSusceptance : this value can be computed from the line reactance and line resistance ; When the value is set to 0, the line is assumed to be HVDC. When all values are set to 0, the computation will be flow based and not account for the linear DC approximation of the AC equations.

Concerning the AC network / AC OPF computations, in addition to the value above, one also needs to specify:

- LineResistance : for each line the resistance
- LineReactance : for each line the reactance
- LineMinAngle : the minimum phase angle allowed for each line (as default –30° is recommended)
- LineMaxAngle : the maximum phase angle allowed for each line (as default +30° is recommended)
- LineRATEA : the thermal limit for each line
- NodeSusceptance : for each bus, the susceptance (as default 0 is recommended)
- NodeConductance : for each bus the conductance (as default 0 is recommended)
- NodeMinVoltage : for each bus the minimum voltage allowed in that bus
- NodeMaxVoltage : for each bus the maximum voltage allowed in that bus

Implemented features

The SMS++ / Plan4Res model can be run in vastly many different configurations and computational modes. Typical interactions are done as follows:

- Modifications to the input data file: allows for the incorporation of dynamic constraints on generation for instance by specifying the optional additional information for each generator.
- Use of solver configuration: allows one to solve for instance the Lagrangian dual, attach different solvers, employ any number of parameters for the specific solvers
- Use of Block config : can be used to trigger variants.

Core assumption

The SMS++ framework is very versatile. It is for instance possible to do deterministic seasonal storage as it also possible to do this while accounting for uncertainty.

One key assumption is that the framework is in principle unit agnostic. It is up to the user to ensure that the units of the various entries are consistent. As an example, one can thus model hydro reservoirs as cascading structures with reservoir volumes in m^3 or as energy, e.g., MWh.

Repository

The SMS++ framework is available here : https://gitlab.com/smspp

A current, yet always to be improved description of the input data is here : https://gitlab.com/smspp/smspp-project/-/blob/master/doc/SMS++%20File%20Format%20Manual/ffm.pdf?ref_type=heads

3.3. Power Market Models

Purpose of the model

POMATWO is an electricity market model designed to determine the optimal electricity supply by minimize system costs on an hourly basis. It incorporates market clearing conditions, market zone-specific merit order curves, grid topology, and network constraints. Using a multi-step approach, POMATWO can simulate both the electricity generation of the day-ahead market and multiple intraday market gates. Built in julia, the model represents an advanced development of POMATO, which also gave the model its name. Within the iDesignRES framework, POMATWO is used to calculate the cost-optimal utilization of generation capacities.

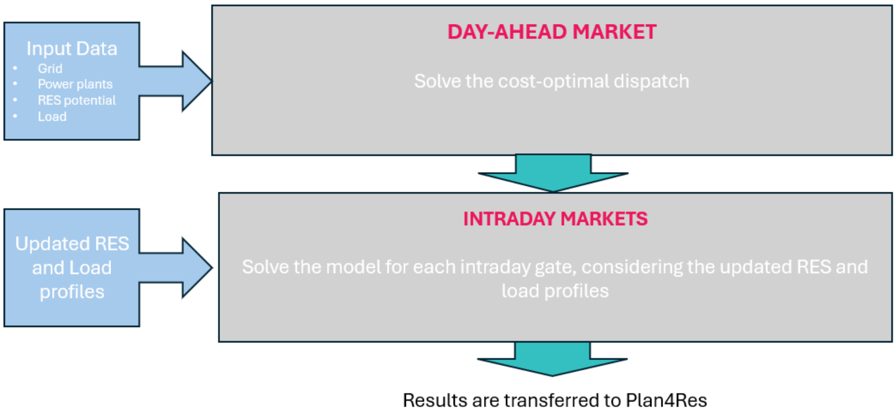
Model design philosophy

The design of POMATWO adopts a multistep approach, emphasizing the structured and systematic representation of electricity markets. The workflow consists of distinct yet interconnected stages. It begins with the simulation of the day-ahead market, where electricity generation is allocated cost-efficiently based on the merit-order principle. This step ensures market clearing conditions are met while minimizing production costs.

In the next step, POMATWO simulates the various intraday market gates that follow the day-ahead market. This phase uses updated time series data that forecast solar and wind generation profiles, as well as load variations, depending on the time to delivery. Based on these forecasts, the model recalculates cost-minimal dispatch and performs redispatch afterwards to reflect updated market conditions. The results are passed to Plan4Res, which performs the final AC redispatch calculations.

POMATWO contains also feature of performing a DCOPF redispatch to address grid constraints. Using DC optimal power flow calculations, POMATWO determines redispatch actions necessary to manage congestion, aiming to minimize the extent of these adjustments and maintain system stability. This feature is not used for the iDesignRES case study, since an AC redispatch is calculated by Plan4Res.

The workflow of POMATWO is illustrated in the accompanying figure, displaying the seamless integration of its components.



Input to and output from the model

To run POMATWO, as it is used in iDesignRES, the following input data is required:

1) Definition of sets
    - Set of market zone
    - Set of time steps
    - Set of nodes
    - Set of generation technologies including solar and wind
    - Set of storages
    - Set of AC and DC lines

2) Parameters required for the model run

Power plants

- Availability of each generation technology at each time step
- Capacity of each generation technology (MW)

Grid

- Capacity of each AC line (MW)
- Capacity of each DC line (MW)
- Incidence matrix of DC lines
- Line susceptance matric
- Bus susceptance matrix
- Nominal transmission capacities between two zones (MW)

Storages

- Inflow of each storage in each time step (MW)
- Storage capacity of each storage (MWh)
- Efficiency of each storage

Cost

- Marginal costs of each generation technology at each time step (EUR / MWh)
- Curtailment costs (EUR / MWh)

Load

- Load at each node at each time step (MWh)

3) Parameters required to calculate the time series to forecast intraday profiles of RES generation and load:

- Number of intraday gates, time of trading session closing, trading schedule per gate
- Hourly day-ahead forecast of solar, wind, and load (MWh)
- Actual hourly production of wind and solar (MWh)
- Actual hourly load (MWh)
- If available, hourly intraday forecasts of solar, wind, and load (MWh)

Output:

POMATWO calculates the cost-optimal usage of generation capacities to meet the load while taking the grid into account.

- Generation of each power plant at each time step (MWh)
- Generation of each power plant at each time step after redispatch (MWh)
- Change of each storage charging level at each time step (MWh)
- Injection at each node at each time step (MWh)
- Net exchange at each zone at each time step (MWh)

These results are available for the day-ahead market at each intraday gate

Moreover, POMATWO calculates possible curtailments, the power flow on the DC lines, possible up and down ramping for each power plant, further storage variables, and the voltage phase angle.

Implemented features

POMATWO employs a multistep approach, solving the day-ahead and intraday markets sequentially. Depending on the specific application, the model can be configured to solve only the day-ahead market or both the day-ahead and intraday markets consecutively. While POMATWO offers the feature to run redispatch calculation, this feature is optional for the user and is not directly included in day-ahead calculations.

Core assumption

POMATWO operates under the assumption of perfect foresight, minimizing system costs while accounting for the market clearing of zonal markets and adhering to the merit-order principle. This approach implies an underlying assumption of perfect competition in the electricity generation market, where producers are presumed to bid at their marginal costs to maximize profits.

The model determines redispatch actions required to address congestion, by minimizing the scale of these adjustments to maintain grid stability. It is also important to note that the model does not include flexibility costs in its considerations.

Repository

The POMATWO model is available under the following link:

https://github.com/iDesignRES/POMATWO

3.4. Natural gas and hydrogen transmission system

Purpose of the model

The Multi-Gas Energy Transition (MGET) model, also referred to as the Multi-Gas Network (MGNET) model, is designed to optimize transport capacities for various gases (natural gas, hydrogen, and carbon dioxide) within a European network. The model was formally known as the Global Gas model (GGM). Its purpose is to repurpose and expand existing infrastructure to accommodate these gases, minimizing investment and operational costs for the period 2020–2050, with five-year steps and representative hours. The model supports iDesignRES by providing insights into cost-efficient network designs, while considering possible future extensions, such as prioritization of hydrogen or large-scale electrolysis. Future applications may focus on refining storage optimization and integrating carbon capture, transport, and storage (CCTS).

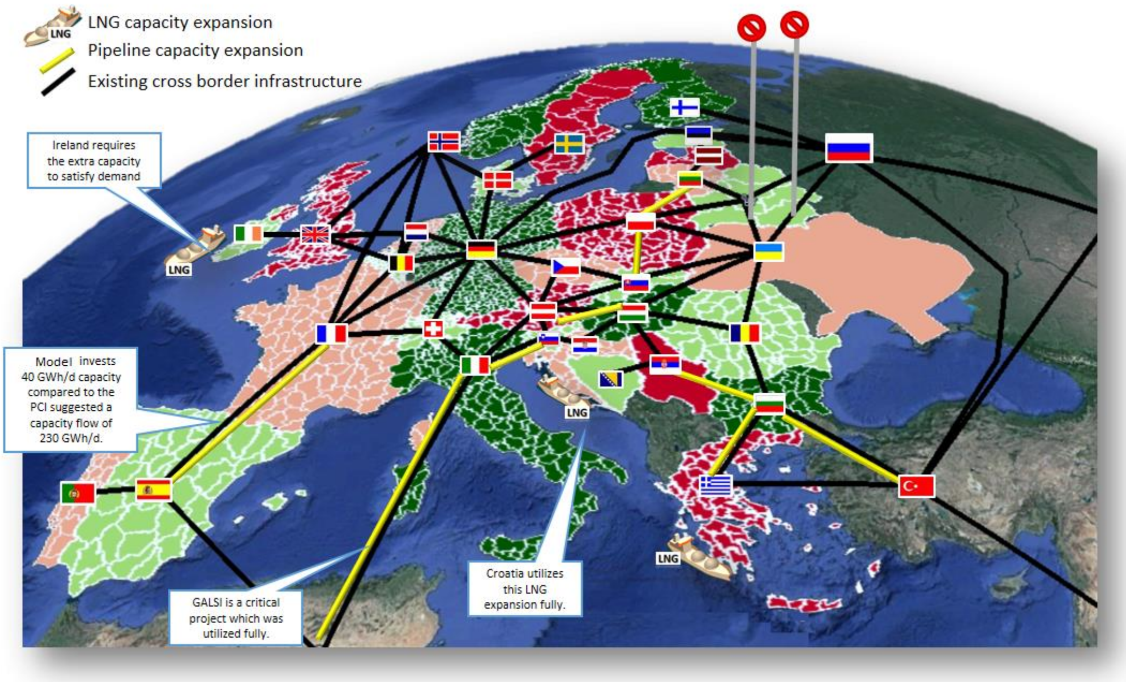


Figure 3.4.1: Illustrative example of model results on pipeline gas flows and new network extensions.

Model design philosophy

The MGET model employs a Mixed Integer Linear Programming (MILP) approach, ensuring cost-efficient transport and repurposing of gas networks. It simulates a European central planner (TSO) deciding on new pipelines, repurposing existing pipelines for other gases, and converting unidirectional pipelines to bidirectional. Costs are assumed to be linear for transportation, investment, and repurposing. Seasonal storage capacities and temporal resolutions (representative hours) are integrated to capture intra-annual variations.

The model is prototyped in GAMS and will transition to R for open-source accessibility, potentially using R Shiny for the user interface. Flexibility in time and spatial resolution ensures adaptability, with initial implementation at the NUTS2 regional level across Europe.

Input to and output from the model

Input

Data category	Sources	Comment
Existing and planned capacities	Internal: GGM existing natural gas data base External: ENTSO-G and other	New: H_2 & CO_2.
Investment costs	Internal: Assembly, GeneSys, GGM External: various sources	GGM data needs to be aligned.
Repurposing costs	Internal: Assembly, or GeneSys External: various sources (NTNU, DIW, Finland)	New
Operational costs & efficiencies	Internal: Assembly, GeneSys, TIMES External: various sources (NTNU, Finland)	GGM data needs to be aligned.

Output

Investment and repurposing decisions, and related costs.
Gas-specific network capacities, for every fifth year.
Gas-specific network flows, for representative hours, every fifth year, and related costs.
if production, consumption, exports, imports, storage interaction are in a range rather than fixed, these will be outputs too.

Implemented features

MGET includes several configurable features, specifically in connection with iDesignRES:

- CCTS Integration: Possible application, depending on scalability.
- Hydrogen/Electrolysis Prioritization: Incorporates supply-demand limits and cost-optimal network configurations.
- Storage Optimization: Enabled but can affect numerical tractability.
- Elastic Demand: Possible but not implemented in iDesignRES to maintain MILP solvability.
- Decarbonization of Harbors/Shipping: Feasibility under consideration.

Core assumption

1. Linear cost assumptions for transport, investment, and repurposing.
2. Dedicated pipelines for each gas type (natural gas, hydrogen, carbon dioxide).
3. Storage modelled as supply/demand nodes with hourly injection/extraction limits.
4. Fixed temporal resolution (representative hours per year) and spatial granularity (NUTS2).
5. Centralized decision-making for a European-wide cost-minimizing TSO.

Implicit assumptions include linear optimization, scalability of network expansions, and neglect of quadratic effects from elastic demand to preserve MILP formulation.

Repository

https://www.ntnu.edu/iot/energy/energy-models-hub/ggm

GitHub: https://github.com/iDesignRES/GGM

4. Energy consumers: industry, buildings, and transport

4.1. Industry

Purpose of the model

The industrial sector is responsible for a large part of the energy, materials consumption and anthropogenic emissions. Even as in the literature of energy system models, each industry has been modelled as a monolithic block, the energy consumption, emissions and materials used are not distributed uniformly across the different processes that each industry must carry out. In this way, the impact of the industrial sector could change considerably if some of the processes are switched but others remain unavoidable. In order to assess this, a database of models to represent energy, materials and emission flows in industrial processes is developed here. The models are fast, accurate and produce results that could be integrated with large scale energy system models.

Model design philosophy

The model developed here plans to go beyond *global emission factors* and build a database of models for each industrial process that could be mixed as needed to model a particular industrial sector including future processes that do not even have emissions factors.

In contrast with the usual engineering models, which are usually based on a set of partial differential equations, the models required for this end should be simpler and faster to compute while attaining enough representativity of the industrial process modelled. Moreover, the methodology to produce these models should be easy for a non-computer scientist to add more industrial processes or to improve these already provided in the database.

For this end, we adopt a combination of different design philosophies:

- **The Genetic Programming philosophy to represent computer code:** In this framework, a program (or model) is encoded as a tree or other similar structure where the mathematical relation between the components is represented. We use this philosophy to encode the relations between the different industrial processes in a way that is easy to write for a non-computer scientist but can be easily manipulated from computer codes.
- **Use of Recurrence Relations to mathematically model each industrial process:** Recurrence relations are easily computable mathematical objects that keep the same expressivity as Ordinary Differential Equations or Partial Difference Equations. They can be written easily both in human form and produce very efficient code.

The main advantage of this approach is that it allows the creation of a **three stage compiler** that takes a data model representing the relation between industrial processes and the mathematical representation of each process and produces a computer code in a computer language. The three stages are:

- **Front End:** will read the data model and will perform syntactical checks (can all the processes be linked? Are they described correctly? Are the constants in the right units? Are variables and contacts following the project nomenclature?, etc.) and produce an intermediate representation of the industrial process.
- **Middle End:** will read the mathematical description of each process and will optimize its representation (for example with constant propagation, simplification of mathematical formulas, solving or expanding recurrence relation, carrying out unit conversion, etc.).
- **Back End:** will finally take the intermediate representation and translate it to source code in a computer language.

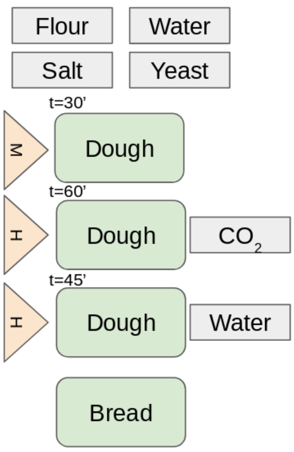
Please note that this philosophy brings us 2 large advantages:

- **It allows us to easily model industrial processes without knowing any computer language.** In fact, it could allow us to create visual interfaces to translate block diagrams to computer models easily.
- **It allows us to use the same representation of the industrial process to produce code for different computer languages in an efficient way**. Please note that only the back end must be changed when porting the models from one language to another.

Input to and output from the model

It is needed to differentiate between the input and output of the compiler to the inputs and outputs of the models produced.

- **Compiler**: the compiler will take as input a description of the industrial processes in a YAML file, following a data model described here, and produce computer code as output (Python code for the moment). For example, the figure below shows a block diagram of the industrial process to produce bread. This block diagram with equations can directly be transcribed to a set of YAML files describing the 3 industrial processes involved. These files can be passed through the compiler and produced computer code ready to import in your experiment (a Python library for the moment).
- **End industrial models**: the input for these models will be the industrial production in the relevant units (for example tons of steel, number of breads, litres of ammonia, etc.). The output of these models will be the materials needed to produce the industrial output, the energy consumed and the emissions. Below can be seen an image representing the bread production. The input will be the tons of bread needed to produce. The model then will give the CO_2 and energy consumed (split into Mechanical and Heat energy). Please note that the model will follow a recipe that could produce a fixed amount of the product. The library will then simply linearly scale to the desired industrial production.



M_{mix}	:=	Mechanical energy for mixing the dough per unit of mass
Fer	:=	Amount of CO_2 generated in the fermentation of the dough per unit of mass
Bake	:=	Amount of H_2O evaporated in the baking of the bread per unit of mass
H(x)	:=	Amount of thermal energy needed to heat the dough x degrees
$Flour^0$	:=	1
H_2O^0	:=	0.5
$Salt^0$	:=	0.02
$Yeast^0$	:=	0.02
1 $Dough^1$	:=	$Flour^0 + H_2O^0 + Salt^0 + Yeast^0$
M^1	:=	$M_{mix} \cdot Dough^0$
$CO_2^{\ 2}$	:=	$Fer \cdot Dough^1$
2 $Dough^2$	:=	$Dough^1 - CO_2^{\ 2}$
H^2	:=	$H(\Delta 30K) \cdot Dough^1$
H_2O^3	:=	$Bake \cdot Dough^2$
3 $Dough^3$	:=	$Dough^2 - H_2O^3$
H^3	:=	$H(\Delta 200K) \cdot Dough^2$
Bread	:=	$Dough^3$
CO_2	:=	$CO_2^{\ 2}$
M	:=	M^1
H	:=	$H^2 + H^3$

Implemented features

At the moment, the following features are present in the compiler:

- Python and SVG back ends are available.
- The data model only allows constant recurrence equations (so the model does not take into consideration the time variable for the moment).
- The optimization does simple constant propagation and rewrite mathematical formulas to reduce the number of operations.

The following features are not present in the compiler, but we are working on them:

- Unit checking and automatic conversion between
- Include full recurrence equations models
- Produce time series of energy, material and emissions. Please note that these time series will not have date indices but just time indices. It is impossible to set up the date when an industry produces their product as these heavily depend on different factors that cannot be easily modelled (like work schedules, industrial needs, etc.).

Moreover, preliminary model of the following industries is included in the repository:

- Cement industry
- Steel production
- Food industry

We are currently working on including more process of these industries as well as in including models for the following industries:

- Wastewater treatment plants
- Manufacturing
- Pulp and paper industry
- Fashion industry

- Data centres

Finally, we have not included for the moment any process to produce the energy requirements or methods to capture and reuse emissions or waste.

Core assumption

At the moment, several general assumptions have been made in the description of the industries.

- Only constant linear models of the process are included at this point. In the next versions it is expected to include time variable ramps and nonlinear descriptions of models when they make sense.
- The constants used to fit each industrial process came from very different sources. It is advised to read the documentation of each process to assess the suitability of the constants before extrapolating values with the model produced.
- The model does not include economy of scale and assumes the input needs scale linearly with the required outputs.

Please note that each industrial process has its own set of assumptions that are described in each of the YAML files.

Repository

The repository for IDR-IIsim could be found at https://github.com/iDesignRES/IDR-IIsim

4.2. Building stock

Purpose of the model

The objective of the model is to simulate the energy performance of the building stock of any region in Europe (NUTS Level2) both for an initial diagnosis and to evaluate different years of the transition period considered in the scenarios proposed. The aim is to cover the building stock for different uses including the residential and tertiary sector with a high degree of disaggregation in both cases.

Besides, the model aims to generate information that provides greater granularity to the building sector models generated in the project for higher scales such as the national scale.

Model design philosophy

In the case of the building sector, when developing new models and functionalities that allow ESM type models (traditionally focused on covering the European and country scales) to reach a regional resolution, it is necessary to find the balance between the agility of calculation and this greater detail of analysis. In this process, it is worth highlighting the potential associated with the use of georeferenced information to capture the specificities of each region in terms of building typologies. This allows a more detailed disaggregation of the building energy model at the country level, capturing aspects such as the number of buildings, surface area, age, or the most specific use for each building typology in the region, as well as their geographic distribution. Traditional methods used for obtaining and processing detailed georeferenced data are applied at smaller scales such as the district or urban scales since they are based on cadastral data. Moreover, they are not easily replicable and automatable for other cities and regions due to their high heterogeneity. This aspect related to the specificity to the case study and the complexity of data preprocessing is an important barrier that makes it unusual to disaggregate national models at the regional level with a high degree of disaggregation of building typologies based on bottom-up data collected.

The developed model aims to help break this barrier by treating and preprocessing geometric and semantic information of each of the buildings (level of detail at the building portal level) in the region. It follows this bottom-up georeferenced information processing approach but starting from georeferenced data available for the whole Europe and developed ad-hoc to cover larger scales such as the regional scale. This information is then used to adapt the energy calculation of the building sector through the use of building archetypes that provide greater detail for each building use. The model performs hourly simulations for given years so that they can be used for initial diagnosis and analysis of potential future scenarios.

Input to and output from the model

<u>Input data:</u>

(a) For initial diagnosis: energy demand (base year assessment).

- Data to be filled in by the user: NUTS Level 2 Code or NUTS Level 3 Code.

- Main data used by the model as input (provided by the model with the option to be modified by the user in case more accurate data are available): Meteorological data (Outdoor dry bulb temperature (hourly), Radiation, Solar gains, heating, and cooling periods); geometry, surface area, age, use of each building. Other building parameters (U-values, H/C base temperature, Window-to-wall ratio, adjacent buildings),

(b) For initial diagnosis: energy consumption calculation (base year assessment).

- Main data used by the model as input (provided by the model with the option to be modified by the user in case more accurate data are available): Shares of fuels/technologies by building type (From statistical data or model results of a higher scale, used for the adjustment), Hourly profiles (for Heating, Cooling, DHW, Occupancy, Lighting, Equipment, kitchen), Installed power (Lighting, Equipment), Equipment performance, Fuel cost, Environmental impact factors.

(c) For the scenarios

- Main data used by the model as input (provided by the model with the option to be modified by the user in case more accurate data are available): Shares of fuels/technologies of the scenario to be simulated (if available from model results of a higher scale, used for the adjustment). Investments/measurement of amount of technology deployed in each sector/type of buildings. For example (for refurbishment low/medium/high) total m^2 refurbished or associated investment, for solar PV total MW installed or associated investment, etc.).

Output data:

-Energy results: Energy demand and energy consumption by building typology: use of buildings/age/archetype/end use of energy/fuel (On an annual basis and on an hourly basis).

-Energy generation results for building integrated solar technology.

-Costs and CO_2 emissions associated.

Implemented features

- The model allows building stock simulations for any region in Europe avoiding most of the building data collection, treatment, and preprocessing.
- The model allows simulations of a given year on an hourly basis (based on the heating degree hours method) for both NUTS Level 2 and NUTS level 3 contained in the region.
- The model generates in a first instance the most relevant information required as input to the energy model in an automated way for the selected NUTS Level 2 region of Europe. Avoiding the user having to contact the different local, provincial, and regional entities in question for the request of cadaster shape files. The characterization obtained is at the portal level of each building in the region collecting the main characteristics in terms of use, sub-use, age, geometry, area and height, as well as their geographical distribution that can be used for finer analysis than NUTS Level 2.
- In a second simulation phase, the model treats the information obtained and simplifies it to the level of archetypes of representative building typologies (according to the form factor) to be simulated for the region.
- The model offers a high degree of disaggregation for both the calculation and the presentation of results based on the following structure: Use - age - archetype - final use – fuel
- The model has an internal database that provides the most relevant data to perform the simulations for any region in Europe. It also offers the possibility of substituting these values for others proposed by the modeler in case more specific information is available.
- Through new simulations of future years, the model allows to evaluate the behaviour of the building stock for different scenarios that consider different degrees of deployment of certain technologies.
- Regarding the coordination with the rest of the models of higher scales that contemplate the behaviour of the building sector, the developed model maintains a coherence with them using a structure of disaggregation of building typologies, final uses and fuels used, as well as allowing the use of the outputs of the simulation models at higher scales to adjust some of the parameters of the regional model.

Core assumptions

- Following the Energy Performance of Buildings Directive[1], static equations are used to determine the heating, cooling and domestic hot water (DHW) energy demand. The methodology is based on the Degree-Days method. However, to obtain a more detailed analysis, the calculation is done on an hourly basis and considers internal gains, solar gains, ventilation losses[2].
- The model does not allow optimization. It is a simulation model that allows the evaluation of prospective exploratory scenarios based on the narratives set for each proposed scenario.
- Once the information is collected for each building, the model groups areas/geometries of buildings based on a clustering of buildings according to their form factor. Three archetypes are considered for each age range of residential buildings and a single representative archetype for each sub-use of the tertiary sector (7 subcategories of tertiary buildings are considered).
- Buildings of industrial use do not fall within the scope of the model. However, their geometric characteristics and geographic distribution across the region are considered to rule out areas available for large-scale solar technology use in the solar module.
- Limitations in terms of technologies or measures considered in the generation of future scenarios: Rehabilitation measures are contemplated differentiating, facades, roofs, and windows (differentiating 3 levels; high, medium, low), replacement of heating and cooling systems, improvement of performances, installation of solar photovoltaic and thermal systems. To include measures related to district heating and cooling systems, they must be introduced as a new technology defining their share of fuel mix, performance, as well as other key parameters representative for the case study.

Repository

https://git.code.tecnalia.com/swt-tecu/idesignres

[1] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union 2010;L153:13–35

[2] Oregi, X., Hermoso, N., Arrizabalaga, E., Mabe, L., Muñoz, I. (2018). Sensitivity assessment of a district energy assessment characterisation model based on cadastral data. *Energy Procedia*, 147, pp.181–188. Available at: https://doi.org/10.1016/j.egypro.2018.07.053

4.3. Transport

Purpose of the model

The purpose of the model is manyfold and can be summarized by the following:

- **Transport sector component model:** First and foremost, it is designed to allow for a regional analysis of the development of energy demand by the transport sector.
- **Regional implications of decarbonization scenarios to transport sector**: It functions as an extension of large-scale energy system models and translates global decarbonization scenarios to the regional transport sector.
- **Stress-testing of transport sector modelling in energy system models**: The increased granularity in the parametrization of the transport sector representation serves further to test the accuracy in the modelling of transport sector as a demand sector in larger-scale models applied in this project.

Model design philosophy

Basic concept: The starting point of the design of this model was the modelling of charging infrastructure requirements, distinguishing these requirements between long-distance transport and transport activity within regions. In terms of geographic resolution, the goal was to decrease the geographic granularity from classic location-allocation models, while still representing relevant granularity to distinguish between long-distance and regional transport. As the adoption of energy infrastructure concerns all transport modes, the model formulation was extended to include multiple transportation modes which are conceptualized as "layers" that are overlapping, all represented with consistent geographic resolution and temporal resolution. The scope of analysis in terms of the transport demand that needs to be serviced, and available transport services (modes, technologies, types of vehicles, fuel types, ...) is set by the user. The reason for this is the following: The transport sector encompasses many different subsectors, including different types of modes, related infrastructures and consumer's that have a limited interference with and relevance to each other.

Time horizon: To include interactions between modes and different drivetrain technologies and model technology shift and modal shift, the temporal horizon is considered over multiple years

Link to energy system models: A focal point in the design was the possibility of introducing local constraints related to the local energy infrastructure and geographically varying energy prices and expansion capabilities for the provision of energy services to the transport sector. Therefore, there are several features in the model that allow these considerations.

Link to transport models: Further, the model implements features that allows the introduction of region-specific parameters of mobility. These are related to the value of time for different transport segments, monetary budget of consumers and travel time budgets. These specific input parameters are very impactful to the choice of mode and technology. Therefore, users are asked to be careful when introducing these parameters.

Cost-optimal optimization: The model is a linear program with a cost-based objective function. The perspective reflected by this is the social planners. While overall cost-optimal pathway for modal and technological shift is determined regarding the total system costs, barriers and social aspects that cannot directly be realistically determined endogenously are introduced in constraints. These include the consideration of the monetary budget of different income classes, values of time for different income classes and expected market shares of different vehicle types (for example, SUVs). Moreover, policy-related constraints are introduced allowing, for example, the ban of newly registering passenger cars with a fossil-fuelled combustion engine as of 2035 within the EU.

Input to and output from the model

Input parameters

In the following, the model parameters for the basic application are listed (optional parameters concerning, e.g. policies/subsidies are excluded here).

Basic model parameters

- Spatial and temporal extend: Time horizon of model and a graph representation of the region of interest
- Selection of modes, vehicle types, drivetrain technologies and fuels.
- Considered route, goods, income classes, region types (f.e. urban, rural. sub-urban).
- Carbon price development

Modes, vehicle types, drivetrain technologies, fuels

- Mode Infrastructure CAPEX
- Mode Infrastructure OPEX
- Initial transport capacity of mode infrastructure (by location)
- Travel speed (by region type)

  .. when mode is represented with vehicle stock

  - Initial vehicle stock structure (by generation of car models)
  - CAPEX of vehicles
  - OPEX costs (excluding fuel costs)
  - Lifetimes
  - Technical parameters: specific consumption, tank capacity, peak fuelling capacity, annual range, occupation/load, possible goods (incl. passengers) to be transported, tank, specific emissions
  - Fuel costs (by location)
  - CAPEX & OPEX of fuelling infrastructure

.. when mode is represented without explicit modelling of the vehicle stock

  - Specific emissions
  - Levelized costs

Routes, goods, income classes, region types

- Origin-destination data
- Monetary budgets, values of time by income class/consumer type/ type of good
- Region-type-specific cost components for the operation of vehicles (e.g. parking fee)

Output parameters

The decision variables of the model are:

- Transport activity by mode, vehicle type, drivetrain technology and route
- Fuelled energy by fuel, region, route, vehicle type and technology
- Vehicle stock by route, consumer type
- Mode infrastructure and fuelling infrastructure capacities by mode/fuel type, by location
- Budget excesses (penalization term for this can be set by the user)

Implemented features

At its simplest setting, the development of mode shares and technology shares for a given transport demand and for a given set of modes and technologies is determined.

There are two different possibilities to model a mode:

- *Levelized cost modelling:* Costs for the mode are considered in a levelized way in €/pkm or €/Tkm. This cost structure neglects granularity within this mode, neglecting specific costs for different types of vehicles, drivetrain technologies and fuels. This simplification allows to avoid issues in the accuracy of a mode stemming from, for example, the lack of specific data in this segment.
- *Stock-based modelling:* Hereby, the mode is represented at a greater detail. The vehicle stock is sized to cover the exogenously given transport demand. For this, an initial vehicle stock needs to be given. Different vehicle types, drivetrain technologies and fuels can be defined. Therefore, the cost structure here is also substantially more granular.

Energy-system related features

There are multiple parameters via which energy-system related aspects can be introduced to the model:

- Energy prices: Average costs for fueling are introduced which may vary throughout the years. The energy prices can also vary depending on the location.
- Supply infrastructure: Costs related to supply infrastructure (e.g. grid connection costs or hydrogen pipeline connection costs for the supply of a hydrogen fuelling station) can be included. Thereby, different supply options and its competition for a fuel can also be considered - for example, the delivery of hydrogen via trucks versus via pipeline installations.
- Fuelling infrastructure capacities and activity: The parameter for rate of the build-up of fuelling capacity for a non-conventional fuel reflect the speed at which its charging capacities are deployed. Concerning the fuelling activity, there exists a flexibility in the fuelling activity when a transport route lies in multiple regions. It is therefore also impacted by geographically varying supply and fuel costs.

Policy-related features

The effect of different types of policies can be analysed with this model. These types include:

- Subsidies for modes and the purchase of vehicles – these are implemented as a parameter that directly reduces the purchase costs of a vehicle.
- Bans of new registrations of vehicle technologies – these are implemented by imposing constraints.
- Goals concerning emissions, minimum/maximum mode shares by region – these are implemented by imposing constraints

Behavioural features

Behavioural and social aspects of different consumer groups are introduced in the following way:

- Value of travel time: This is a measure that is typically calibrated by detailed transport models. The subjective value of travel time is introduced to consider variations in the willingness to pay for an improvement in time efficiency of a transport service.
- Monetary budget: Depending on the type of consumer of transport services, different monetary budgets exist for the investment in new vehicles.

Core assumptions

- Cost-optimality (monetary budget, expected market shares) - as the regional scope of this is too granular to accurately model these – to counteract these effects, constraints and granularity of different consumer groups is introduced.
- An important simplification that is done in this model is connected to the travel demand. This is an exogeneous input to the model. With this, no rebound effect of the deployment of infrastructures and no effect of mode and technology choice and costs on travel demand are considered.
- Availability of different vehicle types ... -> constraints imposed that can limit this based on an assumption from insights of other scientific literature / or the output of other model
- Vehicle possession vs. Income class vs. Purpose of trip (marginal benefits are expected)
- Lengths of connections between regions are assumed to be consistent, i.e. also the infrastructures.

The simplifications of the model described above are also potential features of the model to be implemented in the model in the future.

Repository

https://github.com/antoniamgolab/iDesignRES_transcompmodel.git

5. Models for dynamic analyses using *EnergyModelsX*

These different models combine several technologies for incorporation into an *EnergyModelsX* model. They will be used directly in the receding horizon framework developed in Task 2.2. All developed models are available as individual packages on https://github.com/EnergyModelsX .

5.1. Renewable energy technologies

Purpose of the model

The following nodes have been implemented to model cascaded hydropower into EnergyModelsX:

1. HydroReservoir represents the water stored in each individual reservoir and their respective inflows.
2. HydroGenerator and HydroPump represent conversion between potential energy in the reservoirs at different altitudes and electric energy.
3. HydroGate represents flows to lower reservoirs due to spillage or other means, such as environmental constraints or irrigation.

Constraints can be set on the hydropower nodes to enforce exact level, or minimum and maximum levels for the reservoir storage, gate discharge, generator/pump power production/consumption, and generator/pump water flow.

In addition, two different battery nodes with charging and discharge efficiencies are included. They differ by one allowing to provide reserve capacity to the electricity grid.

Model design philosophy

All nodes are modelled as subtypes of the different nodes introduced in *EnergyModelsBase (EMB)*. This implies that the overall design philosophy follows the design philosophy of *EMB.* The individual nodes are introduced through multiple dispatch within the framework of *EMB*. A core change in the philosophy is that the input and output of the hydro power technologies are no longer explicitly stated. Instead, they are incorporated through explicitly stating electricity and water resources. The incorporation of the scheduling constraints for hydropower is based on multiple dispatch to provide a reusable feature and add only the relevant constraints. The different types of hydropower nodes must be coupled with each other to represent a hydropower system. They present a drainage basin in which water flows from higher reservoirs to lower reservoirs through either gates or generators.

The battery nodes are implemented with different modes for modelling the lifetime. New modes can be introduced by a potential user through developing new methods without requiring changes to the core structure of the module.

Input to and output from the model

The individual technologies require different input data:

HydroReservoir	***HydroGenerator***	***HydroPump***	***HydroGate***
Capacity	Capacity	Capacity	Capacity
Inflow to the reservoir	Variable OPEX and/or fixed OPEX	Variable OPEX and/or fixed OPEX	Variable OPEX and/or fixed OPEX
Stored resource	Water resource and electricity resource	Water resource and electricity resource	Water resource

Optional schedule constraints (level)	Energy equivalent or power-discharge points that describe the conversion to electric energy	Energy equivalent or power-discharge points that describe the conversion from electric energy	Constraints schedule constraints (discharge)
	Optional schedule constraints (power and/or discharge)	Optional schedule constraints (power and/or discharge)	

Within the operational analyses, key output data will be the operation of the technologies provided at a given capacity and system topology, including storage of water in the reservoirs, discharge/pumping of water between reservoirs and conversion to/from potential and electric energy.

Implemented features

The nodes are implemented to allow for operational analysis, while investment analysis is subject to future work. Large scale reservoirs typically require water values as inputs to represent the value of storing water at the end of the planning horizon. This will be provided as a part of the assembly tool in Task 2.2.

The implementation can model cascaded hydropower, where the relation between power output and flow rate for generators and pumps are given by the so-called PQ-curve. The current implementation does not account for change in power due to varying head in up- or downstream reservoirs since it is a non-linear relation. The current implementation also considers gate discharge as an operational decision, hence state dependent flow such as tunnels and weirs are not accounted for.

The implementation for battery life includes both an infinite life without a degradation of the storage capacity and a cycle life in which the storage capacity has a lifetime given by the number of charge cycles and a capacity which experiences linear reduction. It is possible to replace the battery stack once it reaches the of its lifetime.

Core assumption

- The water resource is assumed to be constant, meaning that water is not produced or consumed in the conversion processes.
- Investments are not included in the current implementation of the hydro power nodes.
- The conversion to/from electric energy in the hydro generator/pump is described by the power-discharge relationship. This can either be a single conversion factor (energy equivalent) or a piecewise linear function (the PQ-curve) created from a set of power-discharge points.
- The PQ-curve has to be concave/convex for the generator/pump and requires a convex problem. The PQ-points are assumed to be relative values to the installed capacity of the generator/pump.
- Modelling batteries with a cycle life does not allow for a change in the installed capacity in individual investment periods. Hence, it is necessary to include a new node for each investment period if the capacity is changing.
- Replacing the battery stack is only possible at the beginning of an investment period when using a multi-horizon time structure.
- The reserve capacity battery requires that the reserve is available for a duration of 1 of an operational period.

Repository

The developed models are available on:
https://github.com/EnergyModelsX/EnergyModelsRenewableProducers.jl

5.2. Hydrogen technologies

Purpose of the model

Hydrogen technologies differ from standard technologies due to their operational behaviour. Hence, they require a specific implementation that is not directly included in *EnergyModelsBase* (*EMB*). The following hydrogen technologies (called nodes in the following) are implemented within the hydrogen module for *EMB*:

1. two differing descriptions of electrolysis,
2. one description for natural gas reforming with CO_2 capture, and
3. two descriptions for hydrogen storage.

All nodes improve the mathematical descriptions of the technologies compared to standard efficiency nodes, and hence, result in more reliable results from the operational point of view.

Model design philosophy

All nodes are subtypes of nodes developed within *EMB*. The nodes are modelled as *NetworkNode*, that is they have both a unidirectional input and output. The storage node is modelled as *Storage* node to include variables relevant for considering the storage level and its changes.

Input to and output from the model

The individual technologies require different input data:

SimpleElectrolyzer* and *Electrolyzer	***Reformer***	***SimpleHydrogenStorage***	***HydrogenStorage***
Capacity	Capacity	Charge parameters (capacity and potentially variable and/or fixed OPEX)	Charge parameters (capacity and potentially variable and/or fixed OPEX)
Variable OPEX	Variable OPEX	Storage level parameters (capacity and potentially variable and/or fixed OPEX)	Storage level parameters (capacity and potentially variable and/or fixed OPEX)
Fixed OPEX	Fixed OPEX	Stored resource	Stored resource
Input resources	Input resources	Input resources	Input resources
Output resources	Output resources	Output resources	Output resources
Load limits	Load limits	Maximum discharge flow relative to charge capacity	Maximum discharge flow relative to charge capacity
Degradation rate	Start-up, shut down and offline parameters (time and cost for each)	Maximum level capacity relative to charge capacity	Maximum level capacity relative to charge capacity
Stack replacement cost	Ramping parameters		The minimum, charge, and maximum pressure of the hydrogen storage
Stack lifetime	CO_2 capture rate		

All input data is technology specific data. Additional investment data can be included if desired. The individual technology descriptions will be included in the assembly tool of Task 2.2. Within the operational analyses, key output data will be the operation of the technologies provided at a given capacity and energy system topology.

Implemented features

The individual nodes are implemented to allow for both operational analyses (with the potential for representative periods and operational scenarios or the utilization of the tool developed in Task 2.2) as well as investment analyses.

The two electrolysis nodes represent a simplified (*SimpleElectrolyer*) and a complex (*Electrolyzer*) implementation. In both nodes, stack replacement is included while *Electrolyzer* nodes also include stack degradation, that is a reduced efficiency dependent on the usage, through the incorporation of a bilinear term.

The natural gas reforming with CO_2 capture node (*Reformer*) considers the dynamic behavior of chemical process. Specifically, start up and shut down of chemical processes both require significant time and result in periods with costs but without production. In addition, due to the integrated nature of chemical processes, minimum operating points and ramping constraints are included.

Hydrogen storage differs from standard storage as 1. there is an upper bound on the potential for the storage charge rate due to physical limitations and 2. the energy requirement for compression is a function of the storage pressure, and hence, the amount of stored hydrogen. The node *SimpleHydrogenStorage* includes the upper bound on the storage charge rate, while the node *HydrogenStorage* furthermore incorporates the energy requirement through two differing formulations, a bivariate piecewise linear representation, and a bilinear term coupled with a univariate piecewise linear representation.

Core assumption

The individual components are implemented using *perfect foresight* within the modelled time structure.

Individual assumptions:

- Electrolyzer modelling only allows for stack replacement at the beginning of an investment period, when utilizing a multi-horizon time structure.
- Electrolyzer stack degradation results in a linear reduction in efficiency.
- Compression requirements in hydrogen storage utilize multi-stage isentropic compression in which the maximum compression ratio in each stage is limited to 2.5. It is furthermore assumed that the efficiency of the compressors is 75 % and the inlet temperature is 25 °C.

Repository

The developed models are available on:
https://github.com/EnergyModelsX/EnergyModelsHydrogen.jl

5.3. CO_2 infrastructure

Purpose of the model

CO_2 technologies have a different description compared to standard technologies. As a consequence, new technologies are included in a specific package for modelling CO_2 infrastructure. The following nodes are implemented in the package:

1. a description and methodology for including CO_2 capture retrofit to existing processes and
2. a CO_2 storage node

Both nodes include new technical constraints for specific features.

Model design philosophy

All nodes are subtypes of nodes developed within *EMB*. The nodes are modelled as *NetworkNode*, that is they have both a unidirectional input and output. The latter is not considered for CO_2 storage nodes. The storage node is modelled as *Storage* node to include variables relevant for considering the storage level and its changes.

CO_2 retrofit utilizes a so-called CO_2 proxy resource. This resource is required to account for emissions from the existing process. It furthermore requires minor changes to the original process description. Retrofit allows for either emitting the CO_2 from the original process or capturing it. It is possible for the model to decide the capacity use, and hence, the amount of CO_2 captured. The CO_2 capture process can furthermore have an energy demand and several different capture designs.

CO_2 storage nodes accumulate the storage level over multiple investment periods, if a multi-horizon time structure is included. They can furthermore serve as CO_2 emission technology for captured CO_2 that is not stored. In this case, neither energy is consumed, nor capacity is required.

Input to and output from the model

The individual technologies require different input data:

CCSRetroFit	***CO2Storage***
Capacity	Charge parameters (capacity and potentially variable and/or fixed OPEX)
Variable OPEX	Storage level parameters (capacity and potentially variable and/or fixed OPEX)
Fixed OPEX	Stored resource
Input resources	Input resources
Output resources	
Instance of the CO_2 proxy resource	

All input data is technology specific data. Additional investment data can be included if desired. The individual technology descriptions will be included in the assembly tool of Task 2.2. Within the operational analyses, key output data will be the operation of the technologies provided at a given capacity and energy system topology.

Implemented features

Both technologies can include different modes of investment. CO_2 retrofit can be implemented with different approaches regarding the source of the captured CO_2. CO_2 can be captured from energy related emissions (through carbon in the energy carrier), process emissions (through carbon in input material, *e.g.*, in the cement production) or both. The *CCSRetroFit* node furthermore allows to only capture CO_2 from the connected original process while any additional energy demand for, *e.g.*, heat production can result in emissions from the process. This approach allows the user to modify their model for different capture configurations

Core assumption

The individual components are implemented using *perfect foresight* within the modelled time structure.

Repository

The developed models are available on:
https://github.com/EnergyModelsX/EnergyModelsCO2.jl

5.4. Thermal energy infrastructure

Purpose of the model

Half of the total energy demand in Europe is for heating, with space heating and process heat for industry as the most dominant demands[3]. Majority of the heat supply is still based on fossil fuels. Electrification with heat pumps and electric boilers is the main path for decarbonization of heat supply, which will increase the demand for electricity significantly. However, electrification and integration of heat and power supply through heat pumps and electric boilers creates also new opportunities for flexibility when heat production is combined with thermal energy storage (TES) systems and/or district heating (DH). DH enables also the utilization of surplus heat from sources such as conventional industries, data centres, and electrolysers, hence reducing the primary energy demand, including the demand for electricity, in heat supply.

Proper modelling of the various components in thermal energy systems, as well as their interaction with other energy carriers, is therefore crucial for understanding the impacts of decarbonized heat supply on the overall energy system. The new package *EnergyModelsHeat (EMX)* serves this purpose, being an important addition to the *EMX* modelling framework for analysis and development of integrated energy systems.

Model design philosophy

Thermal energy has the special feature that the quality or usefulness of the energy depends not just on the amount but also on the temperature level. The new package *EMH,* which builds upon the standard components from *EMB,* includes therefore a new resource, *ResourceHeat*. *ResourceHeat* extends the abstract type *Resource* from *EMB* with an additional field for supply and return temperature, enabling to include temperature dependency in technologies for distributing, storing, utilizing or generating thermal energy. *EMH* includes the following thermal energy technologies:

1. District heating (DH) pipe
2. Thermal energy storage (TES)
3. Heat pump
4. Heat exchanger

DH pipe is implemented as a link, heat pump and heat exchanger are network nodes and TES is a storage node.

Input to and output from the model

The individual thermal energy technologies require different input data:

DH pipe	***Heat pump***	***Thermal energy storage***	***Heat exchanger***
Length in [m]	Capacity	Charge parameters (capacity and potentially variable and/or fixed OPEX)	Capacity
Heat loss factor in [W/(m*K)] or [kW/(m*K)] etc., depending on the unit of energy	Capacity lower bound	Storage level parameters (capacity and potentially variable and/or fixed OPEX)	Variable OPEX
Ground temperature in [°C]	Source temperature in [°C]	Stored resource	Fixed OPEX

[3] Heat Roadmap Europe (2017). Heating and cooling facts and figures.

Input resource	Sink temperature in [°C]	Heat loss factor as a fraction between [0,1]	Input resources
	Carnot efficiency as a fraction between [0,1]	Input resources	Output resources
	Input (low-temperature) heat resource	Output resources	Supply and return temperatures for surplus heat
	Input power resource		Supply and return temperatures for district heating
	Variable OPEX Fixed OPEX		Minimum temperature difference ΔT_min

Implemented features

The individual nodes are implemented to allow for both operational analyses (with the potential for representative periods and operational scenarios or the utilization of the tool developed in Task 2.2) as well as investment analyses. The implemented features of the different components are as follows:

- **DH pipe** models the transport of heat in the form of hot water or other fluid in heating networks. DHPipe models the flow of energy from a source to a sink, not water/fluid, and the heat losses are calculated based on the supply temperature of the inflowing ResourceHeat, together with the ground temperature, pipe length and a heat loss coefficient.
- **Heat pump** allows the conversion of low temperature heat to high(er) temperature heat by utilizing an exergy driving force (e.g. electricity).
- **Thermal Energy Storage** is a generic model for storing heat, and functions similarly a RefStorage from EMB with the additional option to include thermal energy losses.
- **Heat exchanger** converts "raw" surplus energy from other processes to "available" energy that can be used in a thermal network.

Core assumptions

- **DH pipe** ignores heat losses in the return flow, following the approach from[4]. Pressure losses are also excluded in the current version of the model; however, pressure losses and the required pumping power are in general very small compared to the heat supply.
- **Heat pump** does not include detailed thermodynamic considerations regarding compressor efficiencies, choice of refrigerant and heat exchanger performance. Since all these factors are included in the Carnot efficiency, there is no way of implementing a load-dependent efficiency of the heat pump. Also, the lower capacity bound does not allow for the heat pump’s capacity to be either zero or between the lower capacity bound and full capacity, as this would introduce a large number of binary variables.
- **Thermal Energy Storage** does not follow a thermodynamics-based approach for the calculation of heat losses. The constant heat loss factor leads to deviations from the actual heat loss function of a TES, but since thermal losses in TES are generally low in relation to storage capacity, this deviation should not lead to significant inaccuracies.
- **Heat Exchanger** assumes that surplus heat may be dumped. The heat transfer can be calculated either by assuming equal mass flow rates in both circuits, or that mass flows have been adjusted to optimize heat transfer.

[4] Kvalsvik and Kauko (2018). Linear optimization of district heating systems. ZEN Report nr 9.

Repository

The developed models are available on:
https://github.com/EnergyModelsX/EnergyModelsHeat.jl

5.5. Transmission infrastructure

Purpose of the model

The core structure in *EnergyModelsX* does not allow for the incorporation of geographical features. Instead, it models a local energy system in which technologies (called Nodes) are coupled *via* Links. These links are directed and it is not a requirement that all technologies are coupled with each other within a local energy system. Transmission between local energy systems is however not included.

This is changed through the geography module of *EnergyModelsX*. This module includes the modelling of transmission infrastructure between different local energy systems.

Model design philosophy

Transmission is included between different *Area*s, each with a potentially different local energy system, through *Transmission* corridors. Each area can have its distinctive selection of technologies, *e.g.*, the technologies outlined in the previous sections. Energy or mass exchange between the individual areas is occurring through a central node representing the exchange point of an area. Transmission corridors can include several different transmission modes for different resources, *e.g.*, hydrogen pipeline transport or high voltage electricity lines.

It is possible to provide new area descriptions which provide, *e.g.*, limits on the net export of a resource from an error. The module is designed that it is also possible to develop new descriptions with constraints for a local energy system like CO_2 emission constraints.

The geography module follows the principles of multiple dispatch. This implies that a user can easily create new area or transmission mode descriptions without having to change the core structure of the module.

Input to and output from the model

The model requires as input the different areas with their local energy system. Depending on the chosen local energy system, a variety of different parameters are required. The individual areas have as input parameters their geographical coordinates to allow for distance calculations.

Transmission corridors require as input the areas they connect as well as the included transmission modes for the corridor.

The input for transmission modes varies for the different modes. In general, it is required to specify the capacity, the relative loss (independent of the distance), operational expenditures, and the transported resources.

The key output from an operational model with the transmission module is to provide an understanding of the exchange of mass or energy between individual regions with local energy system. This implies specifically import and export to a given region as well as the energy requirement for transport mass or energy between different regions.

Implemented features

Two different area types are implemented:

1. a simple area without any limits on exchange of mass or energy between areas and

2. an area in which it can be specified that it has to export in every operational period at least a specified amount of energy/mass.

Three different transmission modes are implemented:

1. A simple transmission mode with relative loss in which the input resource is the same as the output resource. The simple transmission mode allows for bidirectional flow.
2. A pipeline transmission mode in which additional resources may be required for transporting energy/mass, *e.g.*, electricity for compression/pumping of hydrogen and CO_2. The input and output resources must not be the same to allow for a discrete implementation of pressure drop. Pipeline transmission modes do not allow for bidirectional flow.
3. A pipeline transmission mode with linepacking. It otherwise follows the implementation of the pipeline transmission mode.

Although support is included for transmission related emissions, this is not included for the specified transmission modes. It is however simple to include this due to the modularity of the module. All transmission modes allow for the inclusion of investment options. These investment options can be different for the same type of transmission mode in different transmission corridors, *e.g.*, discrete investments for hydrogen pipelines between Western Norway and Northern Germany and semi-continuous investments for hydrogen pipelines between individual local energy systems in Germany.

Core assumption

The geography module only provides a core structure which can be extended by the user. Hence, the number of core assumptions is reduced. However, *EnergyModelsX* uses *perfect foresight* within the modelled time structure. In addition, the following core assumptions are included:

1. The loss calculation, variable operating expense, and energy requirement in pipelines are relative to the transported amount of energy or mass, but not the distance. This allows the user to use non-linear routines for calculating the exact cost for a given transmission corridor.
2. The fixed operating expenses and capital expenditures are relative to the capacity, but not the distance. Again, it allows the user to specify non-linear functions in the pre-processing routines.

Repository

The developed models are available on:
https://github.com/EnergyModelsX/EnergyModelsGeography.jl

6. Detailed technology models

These models are detailed models of the individual technologies. They will be used as input for the model developed in Task 2.2. Within Task 2.2, they will be sampled to provide the required profiles, capacities, and operational expenses for the receding horizon framework.

6.1. Nuclear power production

Purpose of the model

The SMS++ framework / Plan4Res model contains an implementation of the usual representation of a thermal unit. Nuclear generation, although flexible to some extent as well, typically has additional constraints. The NuclearUnitBlock implements these in some representation. Future representations could include more specific constraints when generating primary and secondary spinning reserves

Model design philosophy

The model equations have been written in C++ in NuclearUnitBlock. These are currently focused on the modulation limits.

Input to and output from the model

The specific new input needed is specified through the modification of the netcdf entry files. Instead of specifying that a given thermal unit is a "ThermalUnitBlock", one needs to specify it as a "NuclearUnitBlock". As a result one needs to specify the following additional information:

- ModulationDeltaRampUp : Power variation beyond which a modulation is considered to take place (when ramping power up)
- ModulationDeltaRampDown : Power variation beyond which a modulation is considered to take place (when ramping power down)
- ModulationTime : the time in between which no two modulations can take place

Implemented features

NuclearUnitBlocks can be included or excluded in any of the overarching computational modes: UC, SSV, Investment, ...

Core assumption

Once again the SMS++ frameworks is unit agnostic. This pertains in particular to the unit of the time steps. As a result, the user should ensure that ramping condition units are consistent with that of (active) power production and the duration a time step may have.

Repository

We refer to § 3.1.6 for the relevant links.

6.2. Combined heat and power (CHP)

Purpose of the model

The main purpose of this model is to evaluate numerically the overall process and economics of converting solid biomass to electricity and heat. The overall process is calculated in terms of the mass and energy flows. The economics is calculated in terms of capital investment (CAPEX), variable and fixed operating cost (OPEX) and levelized cost of energy. The implementation of this model aims to extend the *EnergyModelsBase* (*EMB*) for including bioenergy technologies, which have been recognized as an important contribution in present and future renewable energy mix.

Model design philosophy

The structure of the model is graphically represented in Figure 6.2.1. The model includes the following main processes: 1) supply, storage and handling of the solid biomass, 2) combustion of the biomass with recovery of the combustion heat for production of superheated steam, 3) direct utilization of the steam for production of electricity in steam turbine, 4) production of heat through extractions from the steam turbine, 5) cleaning of the raw flue gas after combustion to remove particulate matter, acid gases and volatile organic components. The capacity of the bioCHP plant is defined in terms of the total power output from the biomass boiler, calculated from the electric power and heat demands.

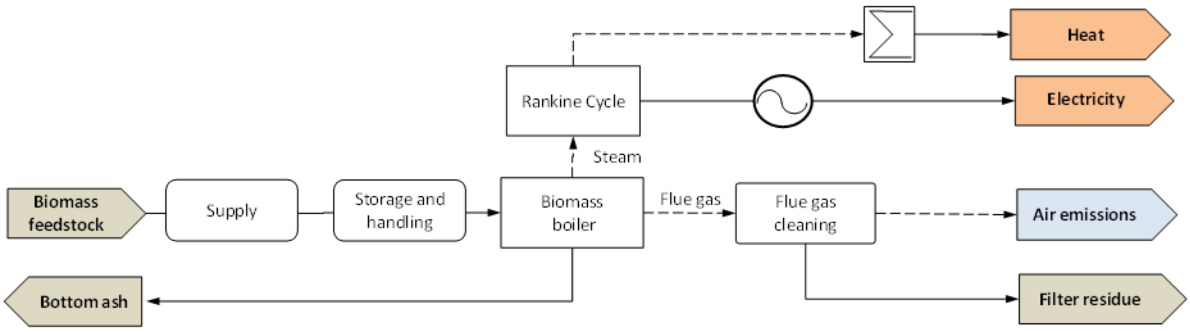


Figure 6.2.1: Schematic representation of the bioCHP model

The model is coded in C++ and includes the following elements:

- **Flows** as objects (classes) defined by mass flow rates, chemical composition and thermodynamics.
- **Processes**: as functions transforming the flows according to physical or thermochemical mathematical models
- **Equipment** as objects (classes) within processes, defined by their type (ex. pump, boiler, heat exchanger, etc) and main design specifications.

Input to and output from the model

Required inputs, as arguments to the EMX node function:

- Name identification (string) and mass fraction and moisture content of each biomass feedstock.
- Time intervals
- Required electric power output for each time interval.
- Heat demands based on thermal power, and outlet temperature and pressure for each time interval

Optional inputs, defined as separate parameters from text file:

- Process specific operational parameters. Ex. excess-air ratio in combustion, boiler steam pressure and temperature.
- Equipment cost parameters. Ex. base year, base purchase cost, scale factor, installation factor
- Prices for consumables and utilities

Outputs, as arguments to the EMX node function

- Required mass flow rate of each biomass feedstock
- Mass and energy flows of bottom ash from the biomass boiler and solid residue from flue gas cleaning
- Mass and energy flows of the cleaned flue gas emitted.

- Mass flows of consumables.
- Main electric loads of the plant
- Capital investment (CAPEX)
- Annual direct variable operating cost (OPEX)
- Annual fixed operating cost (OPEX)
- Levelized cost of energy production

Optional outputs, exported from the model as text file:

- Quantified mass and energy balances
- Energy production efficiency
- List of electric loads
- List of equipment installed cost
- List of variable and fixed operating costs

Implemented features

The main implemented features are:

- Supply of different types of biomass feedstock from multiple sources
- Specification of multiple heat outputs (as steam or district heating) defined in terms of thermal power, temperature and pressure.
- All equipment costs are calculated non-linear using scale factors.
- All optional inputs defined above are imported from text file to allow model users to defined other values. Ex. Equipment cost parameters, prices for consumables and utilities.

Core assumption

- All material and energy flows are calculated assuming state-state behaviour of all processes.
- The steam turbine power outputs are calculated assuming constant isentropic efficiencies for each stage.

Repository

EnergyModelsHeat.jl/submodels/bioCHP_plant at main · EnergyModelsX/EnergyModelsHeat.jl

6.3. Solar modelling

Purpose of the model

The solar power model provides time-series of annual thermal energy generation in Concentrating Solar Power (CSP) plants and electrical energy generation in large Photovoltaic (PV) plants on hourly basis, for a given NUTS2 region and a specific amount of investment in €, in MWp or in m2 for each of these technologies: CSP and PV. These profiles are provided aggregated at NUTS2 level and disaggregated at NUTS3 level, as well as the annual operational expenditures of both technologies.

Model design philosophy

The model firstly establishes the required area to deploy the given investment in each technology. Then, the most suitable available areas in the given region NUTS2 are selected. Once potential areas for each technology in each NUTS3 region are categorized by intervals of 100W/m^2 of Global Horizontal Irradiance

(GHI), those with higher GHI are selected until reaching the area, power capacity or investment required by the user at the input.

Since CSP technology requires higher solar radiation, CSP technology is prioritized when selecting the locations. Considering the solar resource on hourly basis of selected areas for each technology, simplified models are used to estimate annual thermal and electrical energy generation. These profiles are obtained at NUTS3 level and they are finally aggregated to provide them at NUTS2 level. The general scheme of CSP and Solar PV components are shown in the figures below.

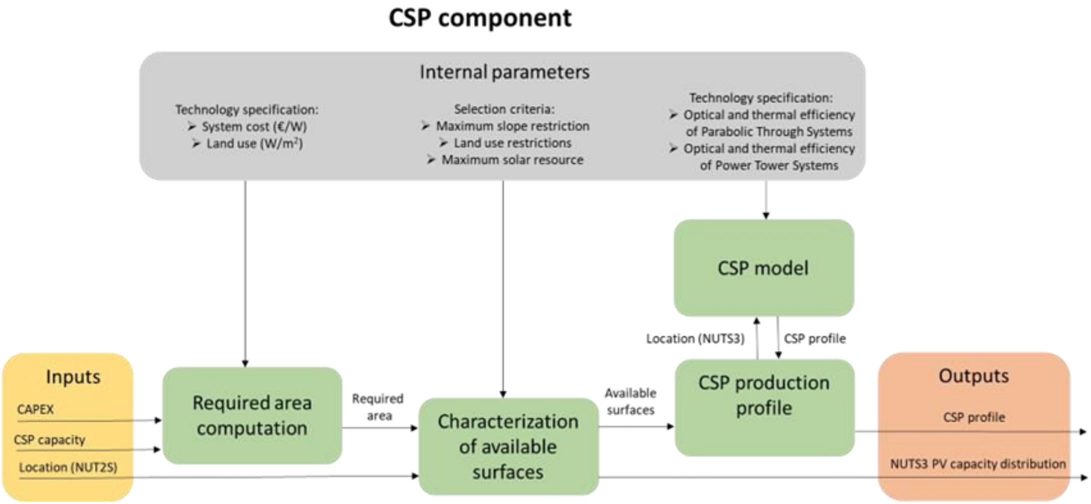


Figure 6.3.1. General Scheme of CSP component.

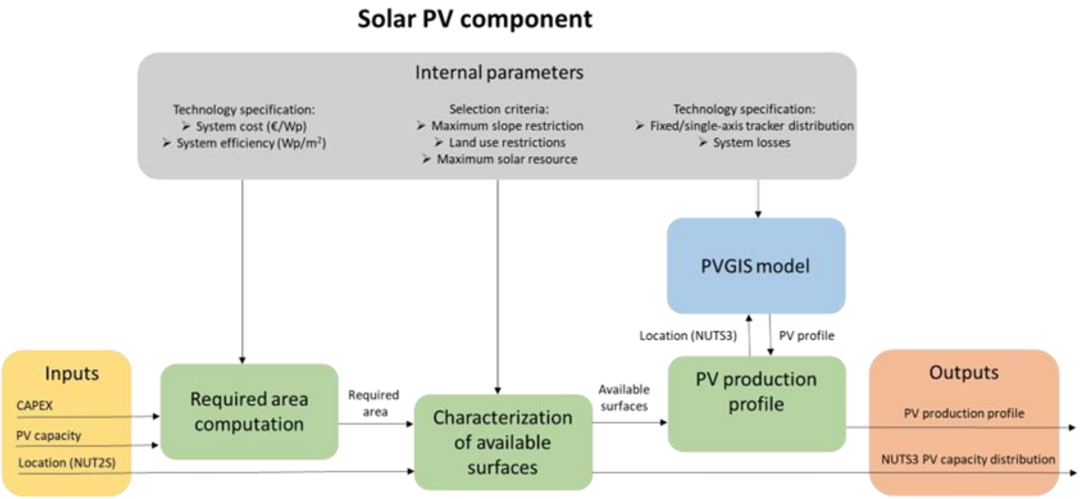


Figure 6.3.2. General Scheme of Solar PV component.

Input to and output from the model

Input:

- NUTS2 region identifier.
- Investment in €, power capacity in MW or area in m^2 to deploy CSP technology in the given NUTS2 region.
- Investment in €, power capacity in MWp or area in m^2 to deploy PV plants in the given NUTS2 region.
- *Optional: Financial and technical parameters of CSP and PV technologies in the market.*

- *Optional: Configuration parameters of areas selection criteria.*

Output:

- Time-series of annual thermal energy generation and electrical energy generation on hourly basis aggregated at NUTS2 level.
- Time-series of annual thermal energy generation and electrical energy generation on hourly basis disaggregated at NUTS3 level.
- Annual operational expenditures of each technology.

Implemented features

- Estimation of required area to deploy given investment or power capacity of CSP and PV technologies.
- Categorization of available areas in intervals of 100W/m^2 of annual radiation for each NUTS3 region complying with selection criteria (maximum slope and land use restriction) for each technology.
- Selection of previously characterized areas with the highest solar radiation until reaching the whole required area, prioritizing CSP and relegating PV in case of conflicts.
- For each selected area estimation of annual thermal or electrical energy generation on hourly basis making use of simplified models of CSP and Solar PV technologies.
- Aggregation of estimated generation profiles at NUTS3 and NUTS2 level.

Core assumption

The main factor impacting on generation profile of CSP and solar PV plants is the available solar radiation. For this purpose, a selection of potential locations with the highest solar resource in the region for CSP and PV deployment is carried out, considering maximum slope and land use restrictions.
For thermal energy generation two different CSP technologies are considered: Parabolic Trough and Power Tower. For both of them specific different optical and thermal efficiencies are considered to estimate the thermal energy available in the solar field. Please note that the thermal energy storage (TES) and power block are not modelled, since these depend on the energy dispatch at the output taking into account existing energy demand and other energy source availability.
For electrical energy demand two different PV technologies are considered: single-axis tracking and fixed mounted systems. For both of them specific system losses are considered, in addition to shallow angle reflection, effects of changes in solar spectrum, and PV power dependence on irradiance and module temperature.

Repository

https://git.code.tecnalia.com/swt-tecu/idesignres.git

6.4. Wind power modelling

Purpose of the model

The wind power model provides time-series for available wind power for a wind farm or group of wind farms for any given geographical location. These can be used as input to the EMX EnergyModelsRenewableProducers.NonDisRES model.

Purpose of the model

The wind power model provides time-series for available wind power for a wind farm or group of wind farms for any given geographical location. These can be used as input to the EMX EnergyModelsRenewableProducers.NonDisRES model.

Model design philosophy

The wind power model is an independent module that essentially generates wind power input data for use with existing models in EMX. The workflow is illustrated below. As the source wind speed data is stored in large files and takes a long time to download from servers, the first step is to collect wind speed data for the required locations and save it to local (temporary) storage. The second, and main step is to convert wind resource data to available wind power data. Both the wind speed data collection and conversion depend on wind power cluster properties, such as location, size and shape of the wind power plant(s).

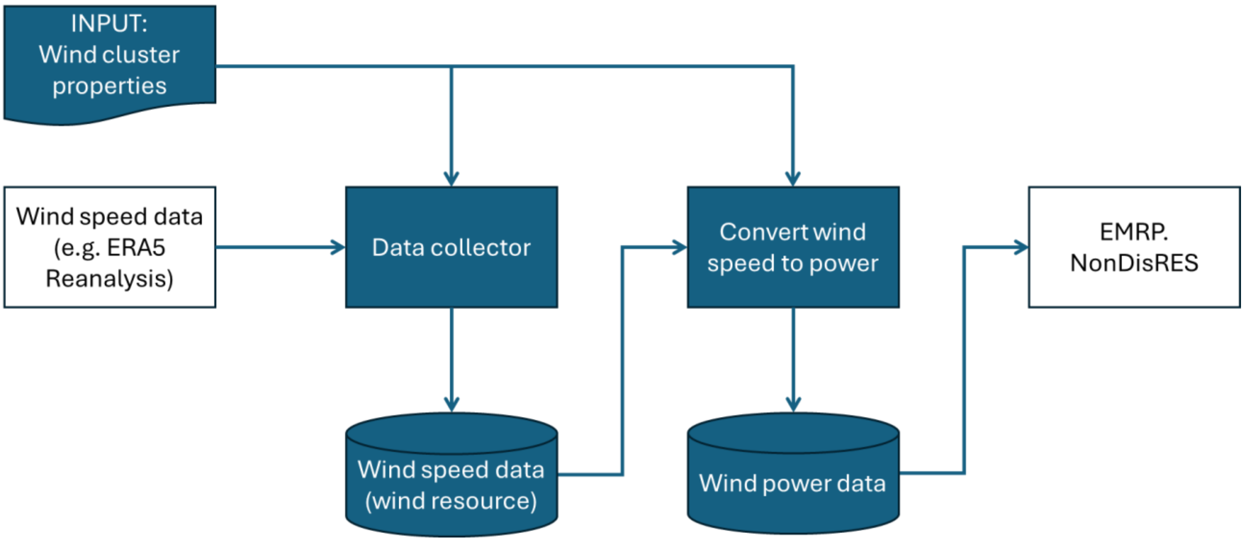


Figure 6.4.1: Schematic representation of the wind power model

Input to and output from the model

Input:

- Wind power cluster properties: Size, shape, turbine height
- Time-series reanalysis data from ERA5 or similar, including wind speed and wind direction, and meta-data such as the height for which the timeseries are provided

Output:

- Time-series giving the aggregated available wind power for a location or area, normalized to give values relative to installed capacity.

Implemented features

- Collection and processing of wind speed data from source data repository
- Scaling wind speed from height provided in source data to height relevant for wind turbines
- Conversion of wind speed to wind power, using a family of effective power curves that represent different types of wind farms. The most important factor for this conversion is the wind speed, but direction of wind vs. wind farm shape is also considered

- Resampling of time-series data to different time resolution

Core assumption

In principle, the total wind power capacity within an area could be modelled by including every single wind turbine, considering wake effects and wind field dynamics, and with the resulting power output from individual wind turbine summed up at the end. However, this involves highly demanding computations that require large amounts of detailed input data, and is not a feasible approach here. Instead, an aggregated modelling is suitable, with the following main assumptions:

- A single input time-series can be used to generate wind power timeseries for a geographically dispersed wind farm or wind power cluster (e.g., a NUTS3 region)
- Many wind turbines within a geographical area can be lumped together using an effective power curve for the conversion from wind speed to wind power.

Repository

https://github.com/EnergyModelsX/EnergyModelsRenewableProducers.jl/tree/dev_windpower

6.5. Battery/Electrochemical storage

Purpose of the model

The purpose of the model is to develop a cost-effective approach for deploying electrical battery storage systems to enhance the secure operation of medium-voltage distribution grids under varying conditions. One of the features of the model aims to address questions, such as: where to optimally locate batteries and what size they should be to maximize operational efficiency and minimize costs. The model has variants that might focus on short-term features of batteries operations (e.g., including degradation or other technical details) or use versions focused on grid allocation by designing battery systems. The latter is the described for this component model.

Model Design Philosophy

The model employs a multi-period optimization framework that simulates up to half-hourly operational decisions, see Figure 6.5.1. Unlike traditional approaches, it incorporates detailed system representations, including non-linear power flow equations, branch capacity constraints, and dynamic electricity pricing. The model can integrate real-world data such as customer load profiles, renewable energy generation (e.g., wind and solar), and market-available battery sizes and costs.

The objective function minimizes the total cost by balancing operational expenditures (e.g., electricity import/export costs) and capital expenditures (battery investment). It determines optimal battery locations using binary decision variables and evaluates battery sizes as both fixed parameters and continuous variables. Key constraints include power flow dynamics, voltage and line current limits, battery state-of-charge intertemporal constraints, and grid connection requirements.

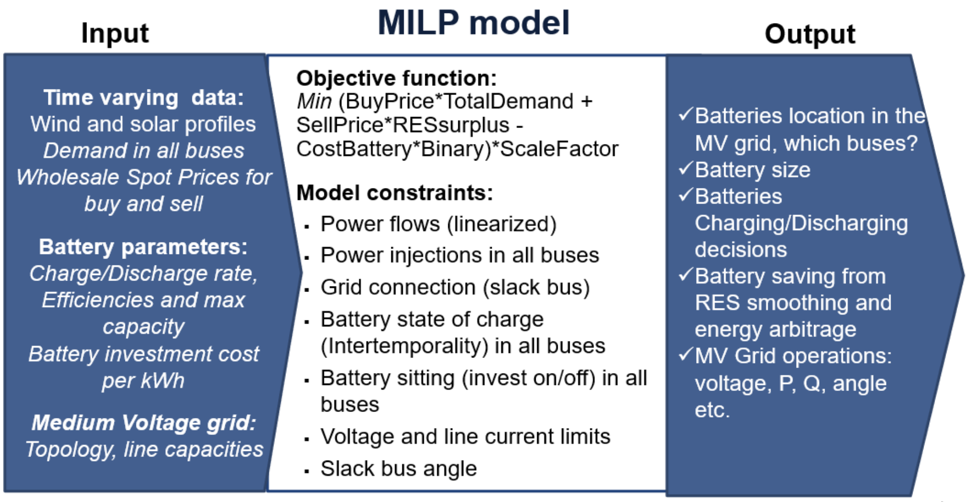


Figure 6.5.1: Overview of the central features on modelling battery interactions in a distribution grid

Input and outputs of the model

Inputs:

- Time-Varying data: Wind and solar generation profiles, Electricity demand at all buses, and Wholesale spot prices for buying and selling electricity or time-of-use tariffs.
- Battery parameters: Charge/discharge rates, Efficiencies (charging and discharging curves), Maximum capacity, and investment cost per kilowatt-hour (kWh).
- Grid physical characteristics: Grid topology (including bus and branch configurations) and line capacities and thermal limits (such as voltage limits, line current limits, and power flow equations).

Outputs

- Optimal battery deployment: Locations of batteries within the grid (specific buses), and sizes of batteries installed at each location.
- Operational decisions: Charging and discharging schedules for batteries over time, and cost savings achieved through energy arbitrage, renewable energy surplus smoothing, and other services.
- Total investment costs for battery deployment.
- Grid performance metrics: Voltage levels, active (PP) and reactive (QQ) power flows, and bus angles across the grid.

Implementation features

- The model has been tested on a modified IEEE 33-bus distribution system, with solar and wind generation allocated based on grid topology.
- High penetration of renewable energy sources (RES) is considered, with the model leveraging RES surplus for cost savings through energy arbitrage.

Core Assumptions

- Batteries are only deployed if their presence reduces overall costs, including operational savings (e.g., energy arbitrage and renewable energy surplus utilization) and capital expenditures. The model assumes perfect foresight.
- The model assumes that RES surplus can be leveraged for cost savings through energy storage.

- Batteries must respect state-of-charge intertemporal constraints, ensuring feasible charging/discharging schedules.
- Voltage and current limits at all buses and branches must be maintained within permissible ranges to ensure grid stability.
- The analysis assumes fixed battery efficiency values for charging and discharging. Other model variants can include more specific electromechanical technological detail such as effect of degradation and other non-linear representations. The assumptions above balance realism with computational feasibility.

Repository

GitHub: https://github.com/iDesignRES/battpower

Other details: https://www.ntnu.edu/web/iot/energy/energy-models-hub/battpower

6.6. Other primary energy sources

The following primary energy sources are important in modelling and planning the transition towards a renewable energy system. These are non-renewable energy sources that might be phase out due to decarbonization policies (e.g., natural gas, coal and oil) or based on national energy strategies (i.e., development of new nuclear power generation and procurement of uranium as non-renewable source). In the iDesignRES project, these are primarily used as input data at the national level or modelled as energy source availability limitations (data) in the European energy system. Hence, these might be inputs for the other component models within WP1 or used in WP2 for transition scenarios in capacity expansion models. The data of these primary energy sources have been collected by large European models part of the project: EMPIRE model (coal), GGM (gas), Plan4Res (Uranium), PRIMES and others. These are detailed as follows:

Natural Gas: The GGM model incorporates detailed modelling of the entire value chain, from production to consumption, and provides insights into how natural gas, as a primary energy source, is produced, traded, transported, and consumed globally. In the value chain representation, the producers are accounted as extraction of natural gas from production wells. The GGM covers over 90 countries, with some large nations divided into multiple production and consumption nodes. For instance, the U.S. has ten nodes, while Russia has three. This granularity allows for detailed analysis of regional dynamics and has dataset modelling primary sources through:

- Production nodes: Each producing country or region is represented by nodes that simulate gas extraction based on resource availability and production costs.
- Transport infrastructure: Pipelines and LNG facilities are modelled to capture the physical flow of gas between regions. Infrastructure constraints (e.g., pipeline capacity) influence trade patterns.

Moreover, the availability of primary sources and the role in global energy systems have been modelled in the EMPIRE model. The latest model dataset has been uploaded to the iDesignRES scenario explorer or as part of EMPIRE git repository. This version is focused on the decarbonization of the European energy system by 2050, particularly in the context of reduced reliance on Russian natural gas. It highlights the use of renewables, hydrogen, and carbon capture and storage (CCS) as primary energy sources and technologies for achieving decarbonization across the power, heat, and industrial sectors. There natural gas plays a diminishing role due to reduced availability from Russia while Liquefied Natural Gas partially replaces pipeline gas but at higher costs.

Coal and oil: These components are used as primary energy sources for back-up capacity or baseload, i. e., coal in some European countries. Oil is used for peak load generation and heavily utilization on end-use sectors: transport, industry, and others. In the energy system model GENeSYS-MOD, data on coal and oil as primary energy sources is gathered and modeled through a combination of exogenous inputs, cost optimization, and detailed energy system representation. Coal and oil data, including resource availability, extraction costs, and market prices, are provided as exogenous inputs to the model. These inputs are typically sourced from external databases or literature on global energy markets. There Coal and oil are modeled as "fuels" within the framework, which act as energy carriers connecting different technologies. For example, coal-fired power plants or oil refineries are represented as "technologies" that convert these fuels into usable energy forms such as electricity or heat. The model accounts for the efficiency of technologies using coal and oil, incorporating losses during conversion processes (e.g., combustion). Likewise, the EMPIRE model presents good representation of coal availability and modelling features when combined with CCS.

Uranium: As the primary component for Nuclear power, this component is mainly determined as fuel supply data. That is, information on uranium availability, extraction costs, enrichment processes, and geopolitical constraints. The Plan4Res model uses Historical performance data of existing nuclear facilities. Also, the PRIMES model includes a comprehensive database of nuclear power plants in Europe, detailing their operational status, capacity, and technological characteristics. The model incorporates parameters for uranium supply, including resource availability, extraction costs, and market prices. These inputs are often derived from external sources like global energy models (e.g., PROMETHEUS) or specialized studies on nuclear fuel markets. Similarly, GENeSYS-MOD uses global datasets to define uranium prices, extraction costs, and emissions data associated with its lifecycle stages, such as mining, milling, enrichment, and fuel fabrication. These parameters are critical for modeling the cost-optimal pathways of the energy system

Repositories:

EMPIRE model:

- https://github.com/iDesignRES/OpenEMPIRE

GGM model :

- https://github.com/iDesignRES/GGM

GeneSysMod model – four scenarios with inputs on primary energy sources:

- iDesignRES scenario explorer : https://idesignres-internal.apps.ece.iiasa.ac.at/

Plan4RES model:

- https://github.com/iDesignRES/Plan4Res-SMS iDesignRES

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