BALMOREL - User guide

Energy system model

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INTRODUCTION

Balmorel

Balmorel is a model developed to support analyses of the energy sector with emphasis on electricity and combined heat and power systems.

The model is suited for energy and environmental analyses of relevant economic and policy related issues as well as technical analyses of power and CHP systems.

The base model was first written for Nordic countries and now used worldwide.

The Balmorel model

Balmorel is a partial equilibrium model which essentially finds the least-cost economical dispatch and capacity expansion solution for the represented energy system.

Results have a robust interpretation as an efficient market solution under the assumption of perfect competition. Both societal and stakeholder perspectives can be analyzed based on the models results. The solution will also represent perfect planning in a non-market system.

North Europe transmission map

Balmorel advantages

Well Recognized – One of only a few models of its kind with a solid representation of CHP

Scalability – same model and fundamental data can be used for detailed “here and now” simulations as well as aggregated “some time in the future” scenarios

Customizable – easy to add new functionalities to address the newest and hottest issues

Generality – separation of model structure and code makes it independent of any specific market/system

Transparency – Fully transparent with regard to model structure, equations and data

Transferable – Open source model means that the entire model can be transferred to stakeholders for inspection or further analyses.

Balmorel project

Balmorel is open for anyone to inspect, use and modify. It is made available free of charge, including a sizable dataset, via the Balmorel website www.balmorel.com. However, running the model requires a licensed version of the modelling language General Algebraic Modelling System, GAMS (www.gams.com).

The Balmorel project is the activity facilitating model and data development by exploiting synergies between projects, users and stakeholders. Much of the functionality of the current version has been developed and refined through successive projects and through collaborative sharing of results, code and data. Development is continuously driven primarily by demands of projects. The flexibility of the underlying modelling system makes it relatively easy to extend the functionality of the model.

Background

Balmorel was originally developed in the period 1999-2001.

The Balmorel project was financed partly by the Danish Energy Research Program. The purpose of the project was to develop a model for analysis of long term development of the electricity CHP sector with an international perspective. The ambitions:

- To model a wide-stretched geography and a long time perspective, with possibilities to emphasize selected topics.
- Flexibility in modeling (not modelling "once-and-for-all").
- An open source model – sharing of knowledge, transparency and collaborations.

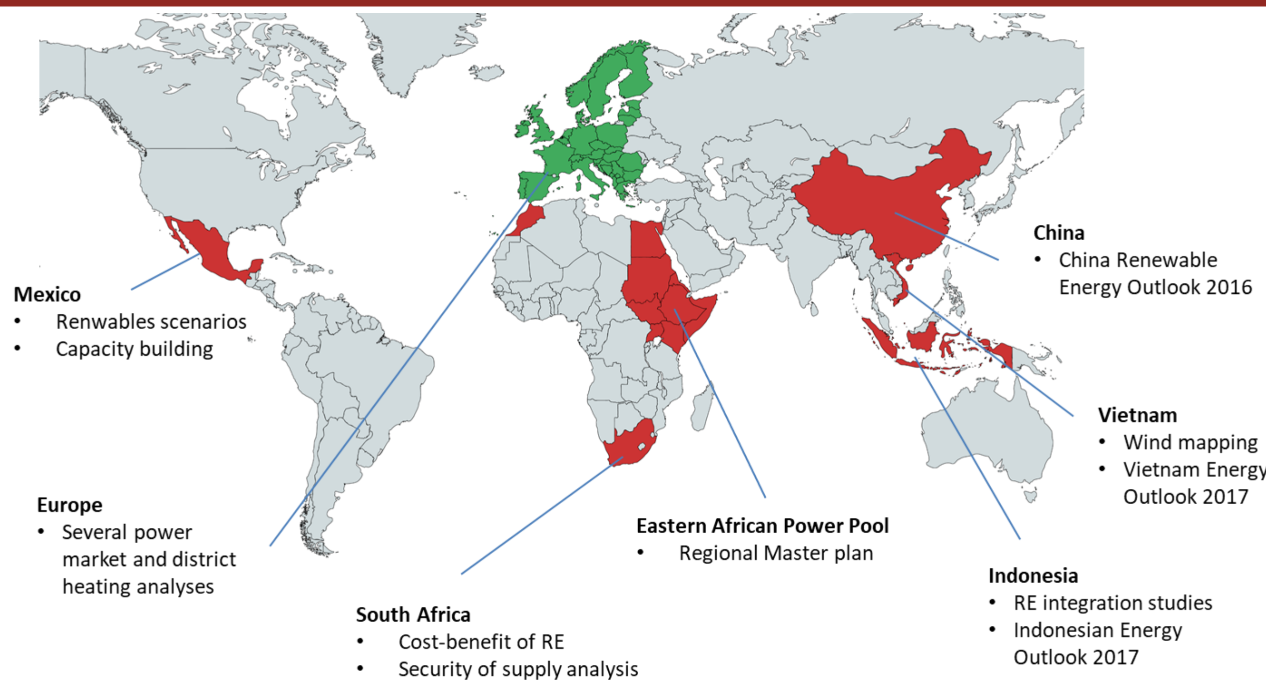
These original ambitions are still preserved in current applications and model versions. Additionally, development has gone toward greater detail and resolution in modelling of time, technology, policy and regulation.

Countries of applications

The Balmorel model has been applied in projects in:

- Denmark
- Norway
- Sweden
- Finland
- Estonia
- Latvia
- Lithuania
- Poland
- Germany
- Austria
- Canada
- Ireland
- Ghana
- Mauritius
- China
- Russia
- Mexico
- Burundi
- D.R. Congo
- Egypt
- Ethiopia
- Kenya
- Rwanda
- Sudan
- Vietnam
- Tanzania
- Uganda
- South Sudan
- Djibouti
- United Kingdom
- Indonesia

Worldwide Balmorel Projects



The modeling system consist of different parts, which are equally necessary to run and use the model. The overall contents of each system component given below.

Data

- Core technical data on electricity & CHP systems.
- Forecasts of electricity and heat consumption.
- Forecasts of costs and availability of energy inputs.
- Regulation and energy policy options for caps, taxes and subsidies of various design.

Model

- Equation for linkages in energy technology system and markets.
- Implementation in GAMS.
- Allows for rapid functionality development and customization.
- Model is translated into standard mathematical problem types.

Solver

- Industrial strength algorithm provides consistent, quick and accurate results.
- Model is independent of solver used within the mathematical problem type.
- Can be run as continuous linear program (core) or in mixed-integer version with unit commitment.

Results

- Flexible handling of results and integration with commonly used tools for analysis and post processing.
- Simple results and log files and error diagnostics with text files.
- Results handling in Microsoft Excel.

Energy system issues

The purpose of the model is to assist in analysing relevant issues for the energy sector. These issues change over time, spurring model development to conform to new requirements.

Balmorel has been applied in analysing relevant challenges for the energy system as exemplified below.

- Security of electricity supply
- The role of flexible electricity demand and demand side management
- Emerging technologies
- Wind power development and system integration
- The role of natural gas
- Development of international electricity markets
- Market power
- Heat planning, transmission and pricing
- Electricity and heat savings
- Expansion of electricity transmission
- International markets for green certificates and emission trading
- Environmental policy evaluation

The model has a general and robust design and can tackle all these issues consistently. Each project usually has special characteristics, which may require innovative approaches to the design of model runs (scenarios) and/or model extension such as new technology options, networks etc. Particularly with respect to policies, there are endless ways in which local schemes need to be handled on a case by case basis.

Types of analyses

Each issue can be analysed from different perspectives with various overarching underlying methodological considerations. The following is a list of archetypical forms of analyses which can be carried out using the model:

- **Market design analyses** – *how market design affects operational decisions, investments decisions and transmission flows etc.*
- **Policy implications/regulatory design** – *impact of regulation or policy on operations, costs, technology choice.*
- **Technical & economic cost-benefit/feasibility** – *looking at an individual project or policy, the costs and benefits can be calculated including multiple possibilities for stakeholder impact analysis.*
- **Operational simulation** – *e.g. Introduction new technical, economic or polity elements to the system and investigating operational and economic implications on units or aggregations of units.*
- **Scenario analyses** – *provides the framework for better decisions at strategic level. This approach finds excellent application in either policy development or strategic planning. The model ensures that scenarios have internal consistency by imposing behavioural logic and an integrated system perspective.*

Utilising the different application possibilities in Balmorel it is possible to investigate various results or consequences for a change in the energy system. Model analyses in general has become an important tool for decision makers acting in complex areas such as the energy sector.

Balmorel simplifications

The scheme below indicates some of the main simplifications applied in the Balmorel model. These simplifications are made both for for keeping results clear and easy to interpret as well as to limit simulation times. Combination with other models can help ensure that the Balmorel results are feasible and reliable with respects to the grid modelling and security of supply.

Examples of model iterations are shown on the left, an overview of model types is shown on the next slide.

Balmorel limitations

Simplified representation of transmission

The transmission grid in Balmorel is reduced to a single capacity between regions. The model therefore does not consider voltages and grid stability but only looks at the hourly energy balance between regions.

Full foresight

For each year, the model has full foresight and can therefore plan optimally with respect of hydro use (optimal reservoir levels) and storages or resource restrictions (e.g. on fuels)

The model also has perfect prediction of wind and solar

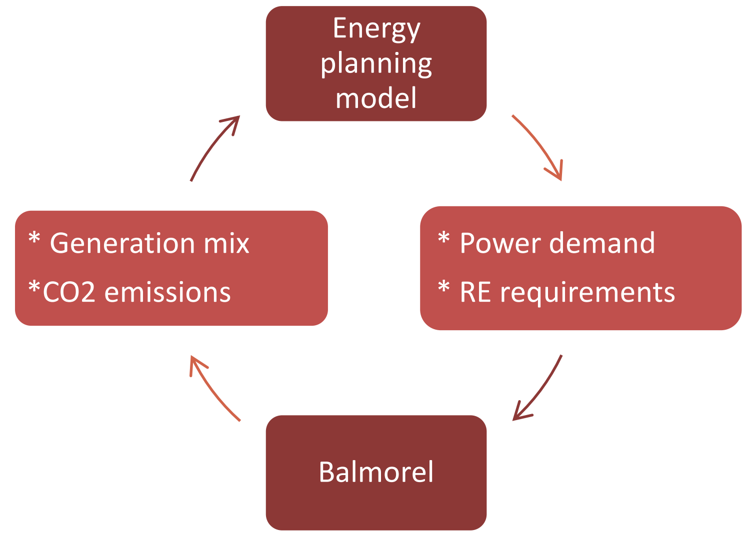
Short-sighted investment optimization

Where the model has full foresight withing one year, it has no foresight with respect to future years and can therefore not anticipate e.g. falling fuel prices or rapidly rising CO_2 taxes.

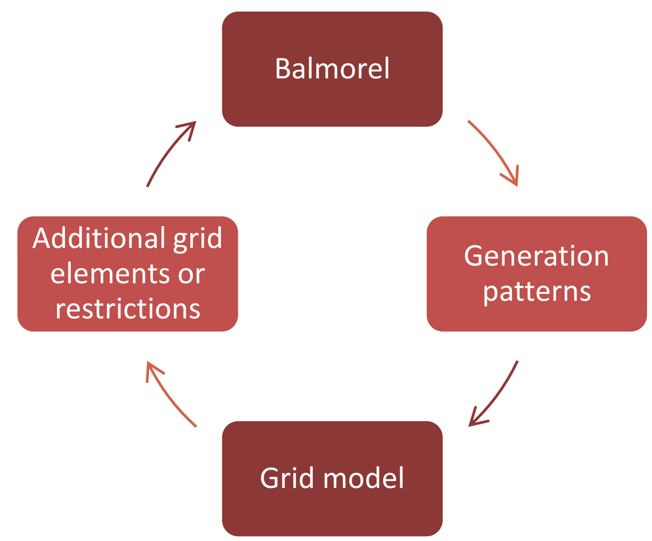
Perfect competition (perfect market)

The model does not see market power. Perfect competition in a liberalised market is in effect the same as perfect planning in a vertically integrated power system

Example of model iteration 1



Example of model iteration 2



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Energy planning – all sectors

Examples: TIMES, LEAP, STREAM, EnergyPlan

- Economic/technical model
- Optimal investment - or simulation
- Interaction of power, heating, transport, industrial sector
- Monthly/daily/hourly resolution

Energy planning – Power/heat sector

Examples: **Balmorel**, PLEXOS

- Economic/technical model
- Optimal investments in generation and transmission
- Optimal dispatch of generation
- Hourly resolution

Operation of the grid

Examples: PSS/E, PowerFactory, Pypower, openDSS

- Technical model
- Operation of the grid (voltage, transient stability, N-1)
- Optimal power flow
- Millisecond resolution

Security of supply

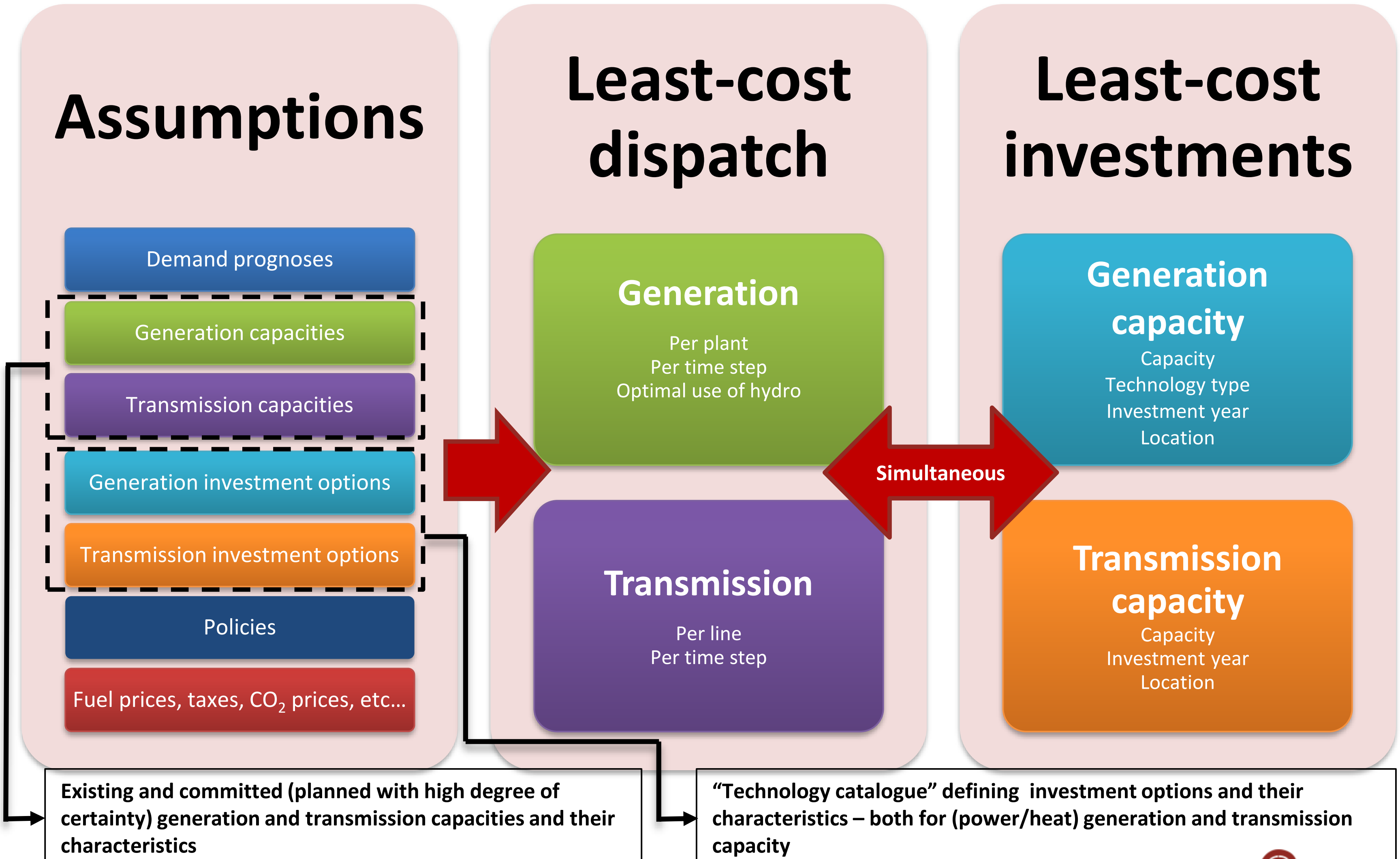
Examples: Sisyfos, Antares

- Stochastic model
- Security of supply
- Probability of availability of power lines and power plants
- Hourly resolution

MODEL FUNCTIONALITY

Simulataneous least-cost optimization inforgraphic

Utilizing the input data provided, the model simultaneously optimizes the heat and power generation dispatch, transmission flow and investments in both generation and transmission capacity. For investment optimization of the generation capacity, the model can select technologies from a ”technology catalogue. This catalogue includes a list of investment technologies and their characteristics as well as the locations of investment possiblilities. Policy restrictions can be implemented for the model to comply with.



Input

The following provides and overview of the most essential types of data needed to run the model. Subsequent pages provide further details. Core input data are located in the base/data directory.

- **Technologies** are defined as either individual units, unit types or aggregations of units. These are associated with technical and economic characteristics, e.g. capacities for production and/or storage (*GKFX*), efficiencies, fixed and variable costs and associated fuels. The main technology data input is in the parameter *GDATA.*
- **Fuels** are defined with associated characteristics: emission coefficients, renewable content and prices. These should be denoted in the parameters *FDATA* and *FUELPRICE* (prices).
- **Resource potentials** or minimum fuel usage requirements can be associated at various levels from countries to single plants (e.g. *FKPOT*, *FGMAX*, *WNDFLH* and more). Seasonal and hourly variations in availability (e.g. wind and hydro) shall be specified (e.g. *WTRRSVAR_S*, *WTRRRVAR_T* and *WND_VAR_T*).
- **Electricity and heat demand** projections are input on regional and area level in *DE* and *DH*.
- **Power transmission capacities** internally in each country (or at sub-country level) and on cross-border interconnections as well as import/export with other countries. Capacities, losses and costs of transmission are defined over a pair of adjacent regions in the parameter *XKINI*.
- **Taxes and subsidies** include national taxes and subsidies on production, consumption or fuel inputs are dependent on geography, fuel types or technology types in *TAX_GE*, *TAX_GF* and *TAX_DE*.
- **Environmental restrictions or penalties** on emission types (CO_2, SO_2, NO_x) in the parameter *M_POL*. Additionally regional policies can be included using add-on modules.

Results

A Balmorel calculation yields results in terms of setting values for quantities and prices (shadow costs) in the hundreds of thousands. To make sense out of this in an analytical content data must be pivoted, filtered and/or aggregated to provide meaningful insights in the problem being analysed. At the core the data output can be characterized as follows:

- **Generation of electricity** and heat associated with units in geographical locations and each simulation time step.
- **Consumption for electricity, heat and primary energy (fuels)** distinguished by geography, units (fuel) and simulation time step.
- **Transmission of electricity** between connected regions
- **Prices of electricity** can be extracted distinguished by the region and time steps in the simulation. Similarly a fair market value of other limited resources can be extracted from (e.g. fuels or CO_2-emission permits) or generated heat.
- **Investments** in electricity and heat generation capacity, transmission and storage capacity can be either extracted endogenous variables when running the capacity expansion model version. Economic rent from location limitations (e.g. for wind), transmission capacity and other capacity scarcity can similarly be evaluated on background of shadow prices.
- **Emissions** from generation and electricity and district heat distinguished by geography, units and time steps.

Results can be aggregated, filtered and further processed to yield and additional level of insight e.g.:

- Unit profitability by determining revenues, direct costs and rent.
- Stakeholder economics decomposition of costs and prices, particularly when comparing two or more scenarios.
- Total costs and benefits from scenario alternatives.
- Sensitivity information from parameter variation.

Geographical dimension

Balmorel uses a layered representation of geography. The simulated system is divided into geographical entities:

- The first layer is **Countries**, for which its possible to formulate politics and aims within these boarders.
- The second layer is **Regions** wherein the electrical system and the transmission are defined. Regions are seen as ‘copper plates’ and without congestion in terms of electricity generation and demand
- The third layer describes **Areas**. With the help of areas, it is possible to specify data influencing generation such as the generation capacity and investment options for generation capacity, full load hours and variation profiles for wind, solar or hydro and fuel prices. Heat demand is also defined per area. Areas are seen as copper plates for heat.

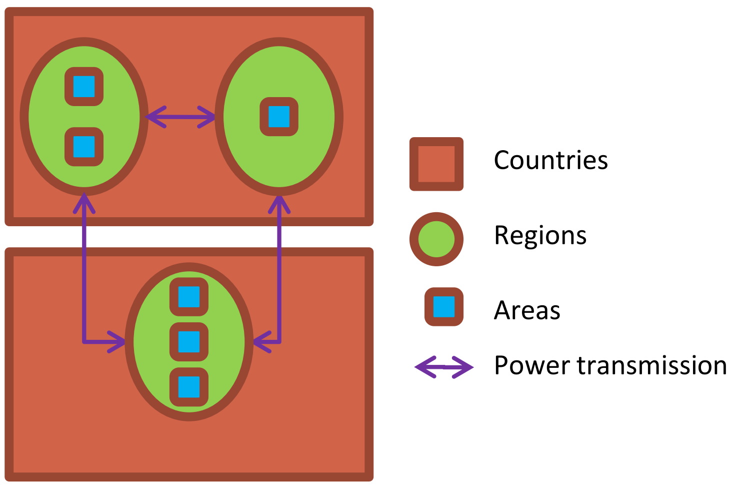
The entities can be abstract or specific names to the represented geography. The approach to the geographical entities provides flexibility in the modelling scope and the structure of the electricity and district heating systems can be customized to any application. This flexible definition of geography enables evaluating bottlenecks of particular interest by scoping the model appropriately.

The geographical subdivision also introduces a flexibility concept in the distinction between countries and the data associated with them, and countries included in a particular simulation.

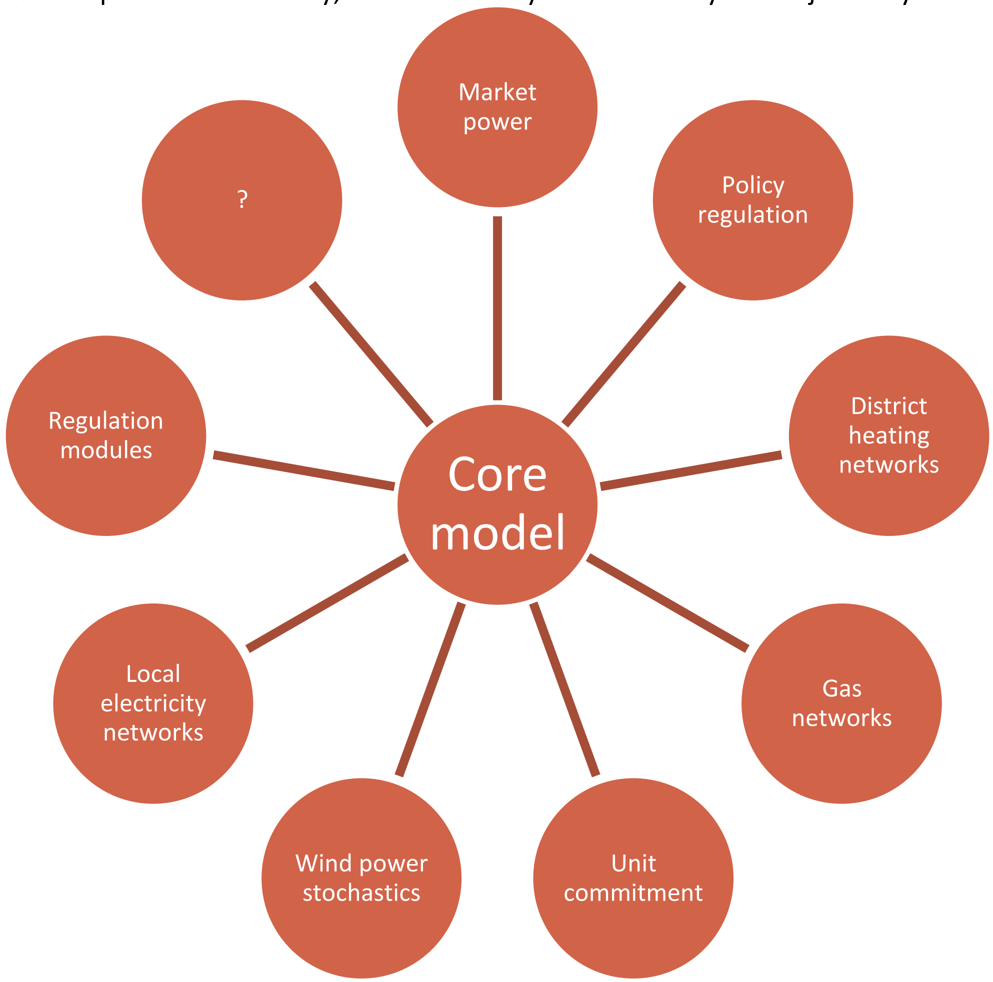
Examples of existing Balmorel data model as divided into Regions.

Europe

Abstract illustration of the Balmorel geographical model



The adaptable framework of the model has led to the useful development of a paradigm for separation of different bits of the model for simple inclusion/exclusion at the users discretion. What is termed as the core model contains the functionality which represents the fundamentals of electricity and district heating systems. The core functionality cannot be "turned off" but its scope is limited by data, e.g. if there is no heat demand present, no heat related equations will be fed to the model solver. From the core it is possible to add expansions termed add-ons designed to add specific functionality, or extend the system boundary into adjacent systems.



This structure enables maintenance of a fairly simple (yet often adequate) model core, while being able to tailor specific functionality for a particular use. The model can subsequently develop without changes to the add-on which can be reactivated at a later time. Add-ons are typically formulated in as a series of include files (*.inc*) located in a folder under the *base/addons* folder, loaded on condition of user activation in the main GAMS file (*balmorel.gms*). Add-on activation is determined by user input to the option file *balopt.opt*.

TECHNOLOGIES

Energy Technologies

Balmorel includes technologies for generation and storage of electricity and district heating. Technology categorizations should be viewed as abstract representations of real world technologies, but are denoted according to familiar technology times. The main categorizations of technologies determine which model relationships (equations) apply to a particular technology. The main technology types in Balmorel are thermal based technologies of which the classifications: Condensing, Backpressure, Extraction, Heat-only are applied; electricity to heat technologies; intermittent generation of which the classifications wind, hydro run-of-river, wave power, solar electric, solar heating are applied; storage technologies which have the classifications are hydro w. seasonal reservoir, short term electricity storage, short-term heat storage, seasonal heat storage.

For any of the above classifications a particular instance of the class of technology can be defined with individual data characteristics such as fuel types, efficiencies, costs etc. The data for these characteristics factors should be defined in the parameter *GDATA*, with the exception of installed capacity and any seasonal dependencies.

The data labels in the technology data table (*GDATA*) are:

- Generation type, fuel used, first year the technology is available for investment, last year the technology is available for investment.
- Fuel efficiency, Cv-value (slope of iso-fuel curve in CHP-Extraction units), Cb-value (ratio of electricity to heat in CHP-mode), SO2 degree of desulphurisation, NOx emission factor, CH4 emission factor,
- Investment cost, variable O&M costs, annual fixed O&M costs, whether investments are possible in the technology type.
- Hours to load/unload storage (relationship between loading/unloading capacity and volume of storage)

While it is possible to denote all these data for any technology type, the specific types may interpret the data slightly differently. The following pages provide particular descriptions of the categorizations and the associated data requirements.

Examples of energy technology and transmission

Thermal power generation technologies

Pure power generation plants are represented by a single technology type labelled condensing technology. Two technology types represent CHP units labelled extraction units or backpressure units.

Key technology data common to all three technology types are:

- Fuel type and fuel efficiency
- Fixed and variable O&M costs, and Investment costs
- Degree of desulphurisation, NOx emission factor

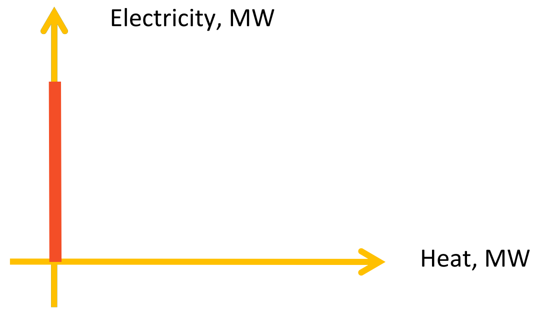
Efficiency is defined as electrical efficiency in full electricity generation for condensing and extraction units but as total efficiency for backpressure units.

Variable operation and maintenance costs are incurred in proportion to generated electricity. *Fixed costs* and *investment costs* are incurred in relation to installed capacity. Only have direct implication on the endogenous model components when running the capacity expansion version of the model.

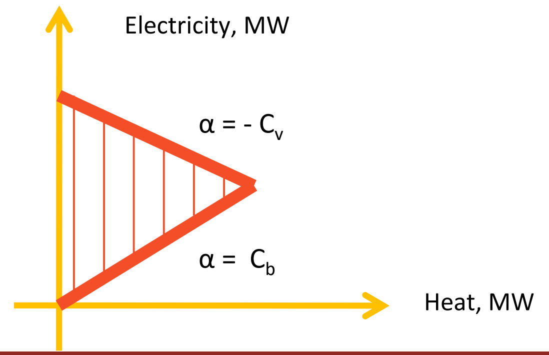
Extraction units are generally larger centralised CHP units characterised by the ability to switch between full CHP mode and full condensing mode.
The *Cv* technology characteristic is slope of the line in which generation moves from full condensing to full CHP mode, i.e. the loss of electricity generation for each unit of heat extracted from the turbine with constant fuel inputs. This number is assumed constant at any generation level.

Technologies which fit the backpressure type could be CHP gas turbines, combustion engines or Stirling engines.
The *Cb* technology characteristic indicates the ratio of electricity to heat generation on a back pressure unit type. On the extraction unit this is the minimum electricity generate as a function of heat generation.

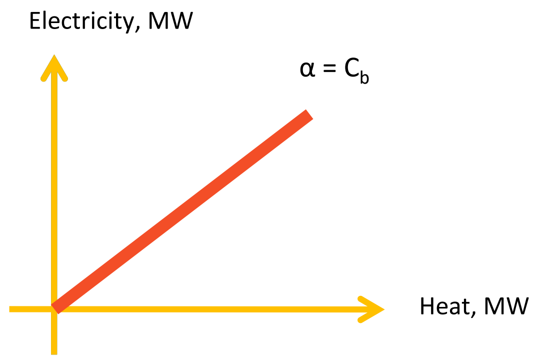
Condensing technology type



Extraction technology type



Backpressure technology type



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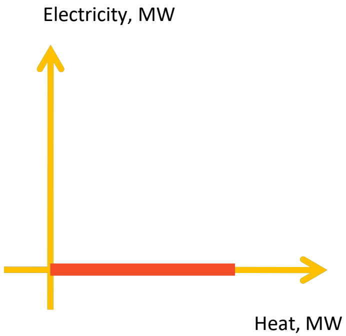
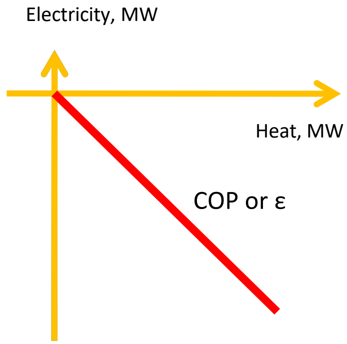
Heat-only boilers

Fuel boilers



Electric boilers



Heat production technologies

These technology types cover heat generation without simultaneous electricity generation:
Heat only units
Example: heat boilers
Electricity-to-heat units
Examples: heat pumps, electric boilers

The types of the following technology characteristics:

- Fuel type
- Efficiency or coefficient of performance
- Fixed costs (per unit of heat generation capacity)
- Variable costs (per unit heat generated)
- Investment costs (per unit of heat generation capacity)
- Capacity (heat generation)

Electricity and heat storages

Both short-term and seasonal storage technologies are represented in Balmorel for heat and electricity, providing system flexibility short-term flexibility (within one season) or to accommodate seasonal variations during the year.

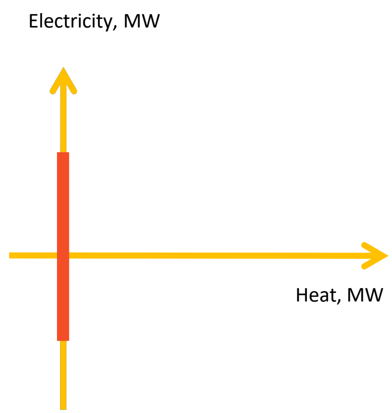
The storages have the following data characteristics:

- Storage capacity (volumetric)
- Loading/unloading capacity (hours to load or unload)
- Cycle efficiency
- Fixed costs (per volume of storage)
- Variable costs (per generation output)
- Investment costs (per volume of storage)

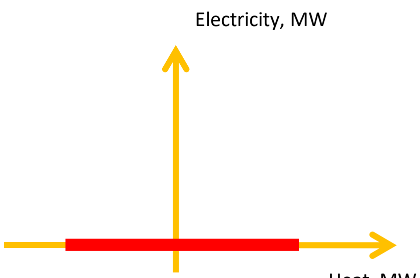
Examples of electricity storage type: pumped storage, batteries
Examples of heat storage type: heat accumulator

Feasible operating region for an electricity and heat storages

Electricity storage



Heat storage



Intermittent generation technologies

Intermittent generation technologies, like wind or solar, require additional data in the model associated with the area of installation rather than the technology type.

The resource data required are:

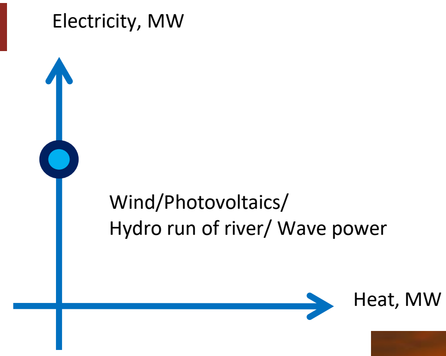
- Full load hours (FLH) over a year and variability of source by hour (VAR_T):
  - Wind: *WNDLH* and *WND_VAR_T*
  - Solar: *SOLEFLH* and *SOLE_VAR_T*
  - Run-of-river hydro: *WTRRRFLH* and *WTRRRVAR_T*
  - Wave power: *WAVEFLH* and *WAVE_VAR_T*

Given these factors and the installed capacity the possible power generation is derived for each time step of the simulation as explained in the profile scaling section. When necessary, the model may select to curtail the technology if it is efficient.

The technology can be implemented with specified:

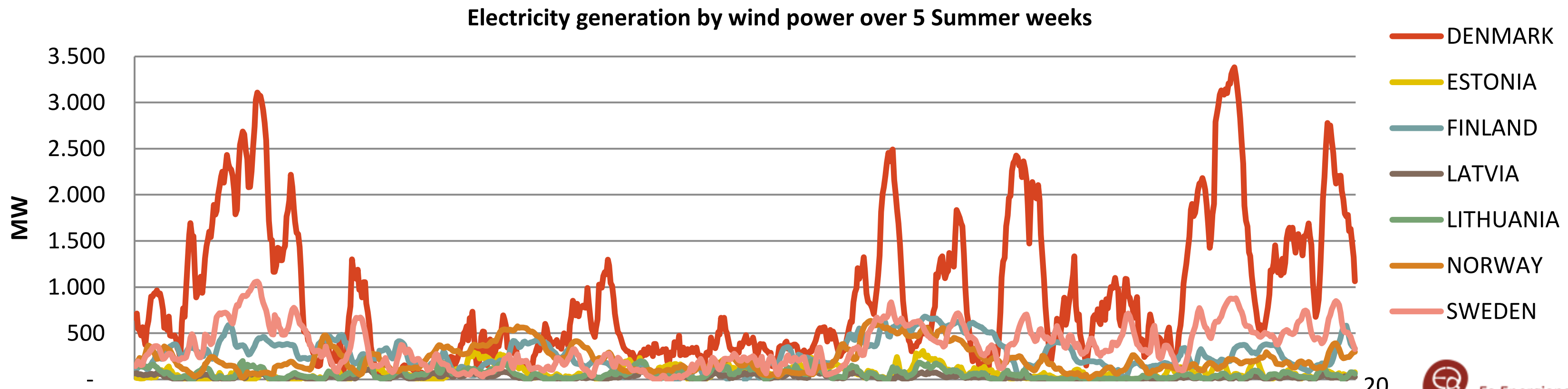
- Fixed and variable O&M costs, Investment costs

In conclusion, developments are being made to add capacity availability to deal with forecast errors in the unit dispatch.



http://magazine.canadiangeographic.ca/Atlas/glossary.aspx?alpha=w&id=352&lang=En

Example of wind generation by hour dependent on wind conditions and installation in a simulation of Baltic Sea countries



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Wind Power

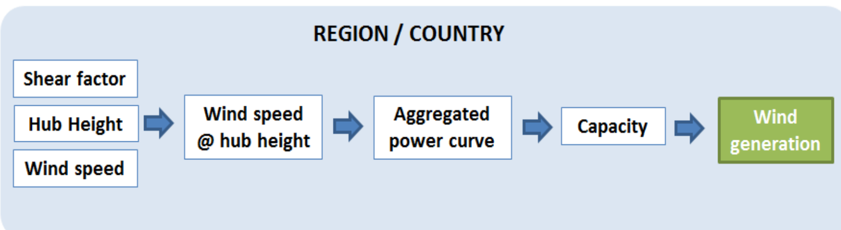
For wind power modelling an alternative to the scaled production profile is available This wind power modelling requires additional data in the model associated with the area of installation rather than the technology type.

The resource data required are:

- Wind speed at given height
- Shear factor

Additional data needed:

- Power curve parameters for wind technology
- Hub height of wind technology
- Smoothening parameter (as the model represents many wind turbines spread over a region)



With this information, the wind speeds at the hub height of the wind technology can be found using the power law:

$$u_2 = u_1 \cdot \left(\frac{h_2}{h_1}\right)^{\alpha}$$

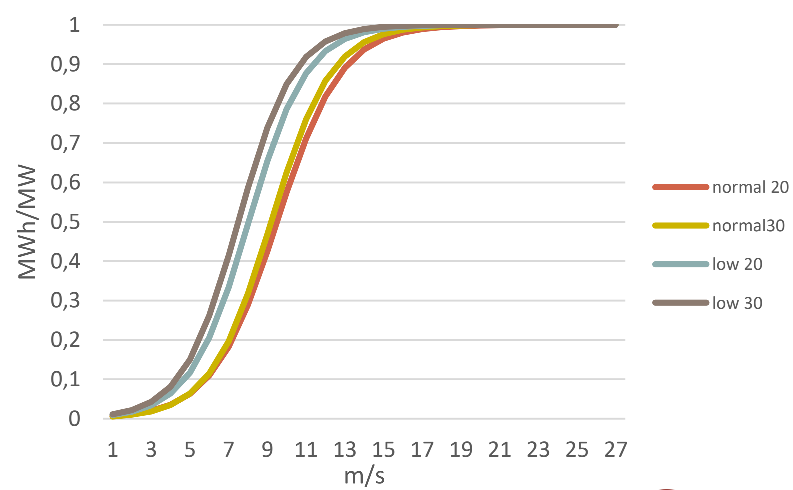
Power curves

With the help of the power curve parameters the power generation of the technology can be found as a modified logistic function:

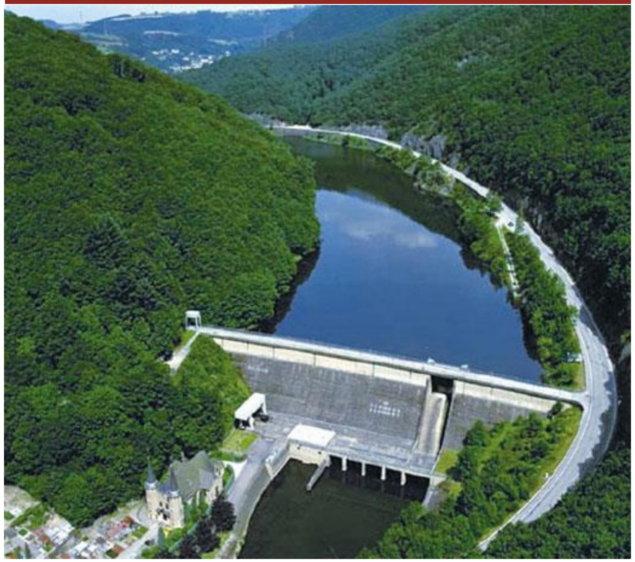
$$P = \frac{\gamma}{1 + e^{\left(-g * K_w * (u - M - \epsilon)\right)}}$$

- u: wind speed at hub height,
- γ: maximum power output reached in p.u.,
- M: wind speed at which the maximum growth is reached,
- g: maximum slope of the logistic curve,
- K_w: smoothening parameter to account for wind distribution in the region,
- ϵ: offset in the speed to represent the effect of real output compared to theoretical power curve from manufacturers.

The benefit of this approach is the possibility to take into account development of wind technologies over the year (for example low-wind speed technologies with higher full load hours) and smoothening.



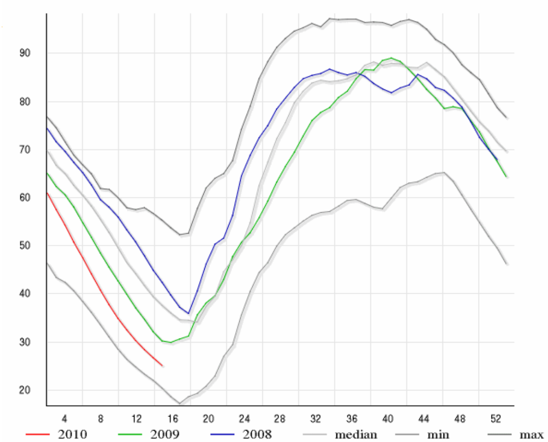
Hydro power with seasonal storage



Hydro Power

Reservoir Content for Norway

Numbers in % of reservoir capacity



The figures represent 97.1 percent of the total reservoir capacity. The total reservoir capacity is 84.3 TWh. Pr. 12.04.2004: 81888 GWh. Min, max and median values for the period 1990 - 2007.

Source: Norges vassdrags- og energidirektorat (NVE)

Characteristics and modelling

The second type of hydro power is the hydro plant with seasonal storage. This shares characteristics with the hydro-run-of-river type, but with added flexibility.

Resource data are required for this technology type:

- Full load hours over a year (*WTRRSFLH*)
- Variation of inflow by season (*WTRRSVAR_S*)

The technology additionally has the standard economic characteristics:

- Fixed O&M costs
- Variable O&M costs
- Investment costs

The storage option works so that any hydro inflow which flows into the system in a given season is either used or stored for future seasons. If there is a surplus of hydro, the storage level for the next week will be higher than the previous week.

Operational constraints can additionally be applied to the reservoir with the parameter *HYRSDS* which importantly is shared by all hydro-with-storage generation capacity within a particular area. These constraints include:

- Maximum volume of the reservoir (*HYRSDRSMAX*) - Seasonal, expressed as % of annual generation
- Minimum level permitted in storage (*HYRSDRSMAX*) – Seasonal, expressed as % of annual generation
- Minimum level of generation on hydro plants (*HYRSDGMIN*) –
- Seasonal, expressed as % of generation capacity

As hydro generation is uncertain and the model is deterministic a risk premium can also be applied to the use of hydro in a particular season. This can be viewed as a top down calibration and can be calculated on the basis of historical electricity prices.

Fuels

Every technology is associated with a fuel type specified by a specific fuel number as a technology characteristic in the parameter *GDATA*. Fuels in the model are however generic entities, i.e. the user must specify the names (in *FFF*) and associated characteristics of the fuel as data input (in *FDATA*).

The characteristics defining a fuel in the parameter *FDATA* are:

- Emission CO2 (kg/GJ)
- Emission SO2 (kg/GJ)
- Emission N2O (kg/GJ)
- Share of fuel considered renewable ([1;0])

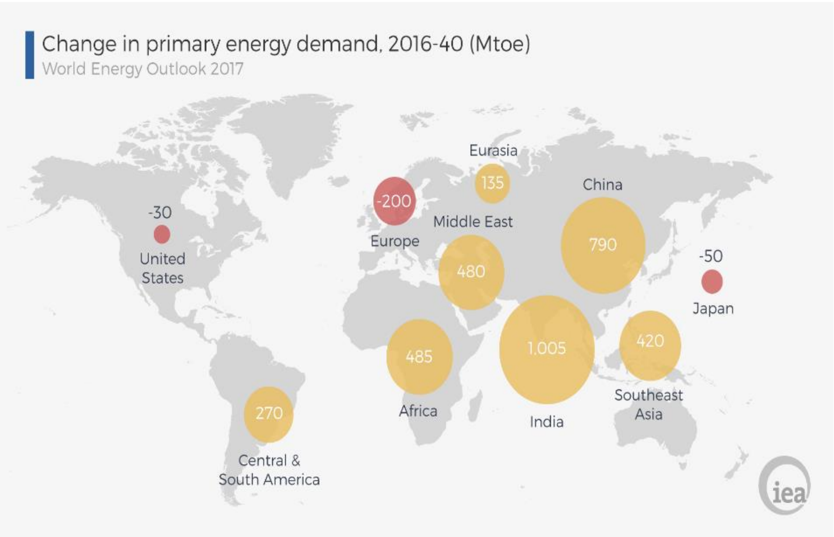
The share of fuel being renewable is used mainly as a medium to aggregate output or in certain policy add-ons.

Example: A fuel defined in Balmorel could be municipal solid waste. This fuel could be considered partly renewable, because it contains both plastic and organic waste.

Investments can be restricted to specified total installation capacities by any of the three geographical entities (countries, regions or areas). The shadow price of the siting limitation equations gives the economic rent per MW of the capacity type.

Fuel consumption is calculated in the model based on the endogenous variables of heat and electricity generation, as well as the technological characteristics of units.

World Energy Outlook 2017



Fuel prices and resource limitations

Each fuel is associated with a price defined in *FUELPRICE*. This contains a price for each area, year and fuel in the simulations.

Furthermore, resources can be limited to a particular quantity for a fuel at any of the three geographical entities (countries, regions or areas. When fuels are limited, the shadow price of the limiting constraint can be seen as a fair market value of that fuel resource.

Alternatively, minimum level of consumption or equality level restriction can be applied. This would also render the option of extracting a shadow value of the resource.

Example: For municipal solid waste this value may be negative reflecting that revenues (market values) for generation of electricity and heat would not cover costs in a particular area.

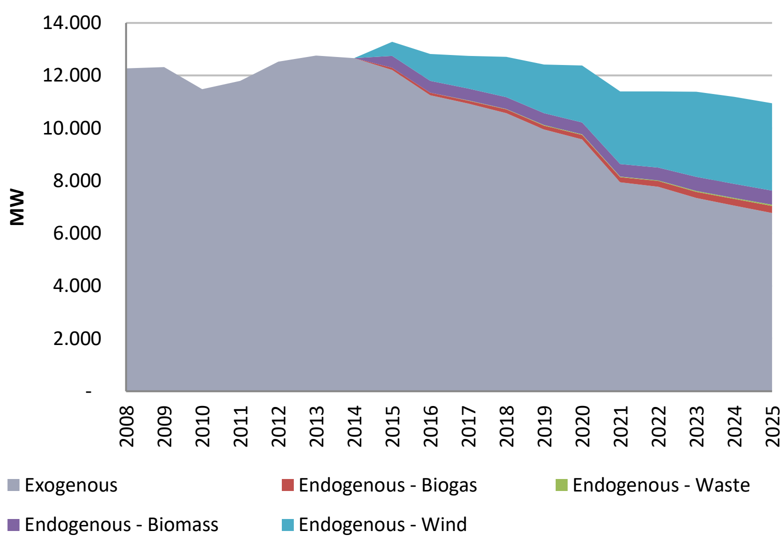
The capacities in Balmorel

The installed capacity in Balmorel can both be exogenous and endogenous. The exogenous capacities are data entered in Balmorel and the endogenous capacities are the model's choice of optimal investments.

All exogenous production capacity for generation technologies should be defined in the parameter *GKFX,* which gives the capacity of a certain technology in a certain area per year.

- Most of the time, this capacity should be **power capacity** (in extraction mode for extraction technologies) in **MW**.
- For heat pumps and heat-only boilers the capacity is given in **heat capacity (MW)**.
- For storage technology the capacity is given in terms of **storage volume (MWh).** Loading and unloading capacities are then defined as hours it takes for full load/unloading in *GDATA.*

Transmission capacities are formulated in the parameter *XKINI*, defining the allowed possible flow between two regions. The transmission capacities can also be defined for each year.



Investments

Future investments can be added exogenously in *GKFX* (or *XKINI* for transmission). These investments are often relatively certain projects and are called 'committed' in this manual.

Another option for investments it to let the model optimise new capacity chosen from a 'technology catalogue'. Model-based capacities are called endogenous.

The model will choose to invest when the needs for additional capacity arise or when there is an economical advantage in installing to displace generation on older technologies, e.g. as a consequence of technological development or the price of fuels or changes in regulation. The model will take the annualised cost of investment into account (annuity factor is an input scalar) in the optimization.

The parameters two dimensional set AGKN defines the investment options for generation capacity (generation technologies per area) and can be set in three ways:

- **Set AGKN directly**
- **Technology types** containing several technologies can be defined in the two dimensional set *ALLOWEDINV_STAND*. These can then be assigned to areas (parameter *INVESTMENTS*)which will be able to invest in all the technologies in the group
- **Individual technologies** can be assigned to areas as investment options in the two dimensional set *ALLOWEDINV*

Transmission capacity will be allowed only between regions for which investment costs are defined in the parameter *XINVCOST.*

Decommissioning

The model can endogenously decommission capacity if it is profitable to do so (by saving fixed O&M costs and annualized investment costs).

Endogenously invested capacity is removed after the lifetime runs out. Exogenously defined capacity should be removed after the lifetime exogenously.

Transmission line capacity will never be decommissioned.

Unit commitment

Unit commitment is a classical topic in the modelling and optimization literature related to power systems, with more than 40 years of investigations and hundreds of publications.

The Balmorel model, by default, overestimates unit flexibility, not taking into account the real-life restrictions on unit operations imposed.

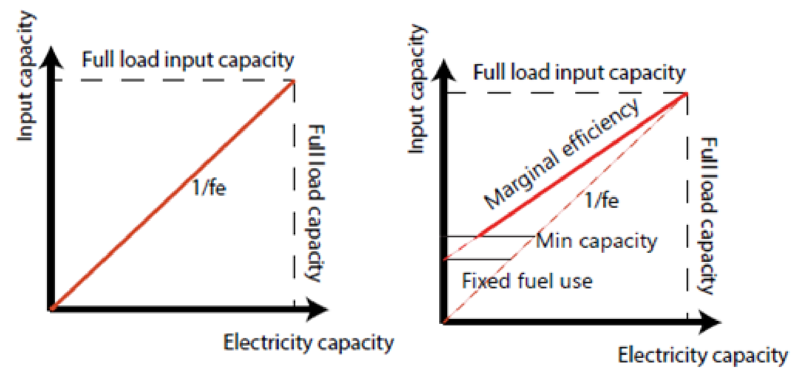
When running with unit commitment, however, the model will take into the following operational restrictions, which are set in GDATA:

- **Start-up costs** (money/MW_{cap}): the cost for starting up a unit
- **Minimum generation** (%): if the unit produces, it must do so at a minimum share of total capacity
- **Online O&M cost** (money/MW_{cap}): the cost for being online
- **Fixed fuel use** (%): the unit uses a minimum amount of fuel whenever it is operating. This amount is expressed as the share of the fuel used at full capacity
- **Minimum up and down time** (hours): minimum amount of hours a unit will stay online/offline after start-up/shut-down
- **Ramp-up and ramp down rate** (% of capacity per hour): the rate at which the generation can increase and decrease per hour

Fixed fuel use

The graph below illustrates the effect on the fuel efficiency of a unit when using the fixed fuel use, unit commitment constraint.

For just being online, a certain share of input capacity is already needed.



Running with unit commitment

To enable runs with unit commitment the following global parameters need to be set to 'yes':

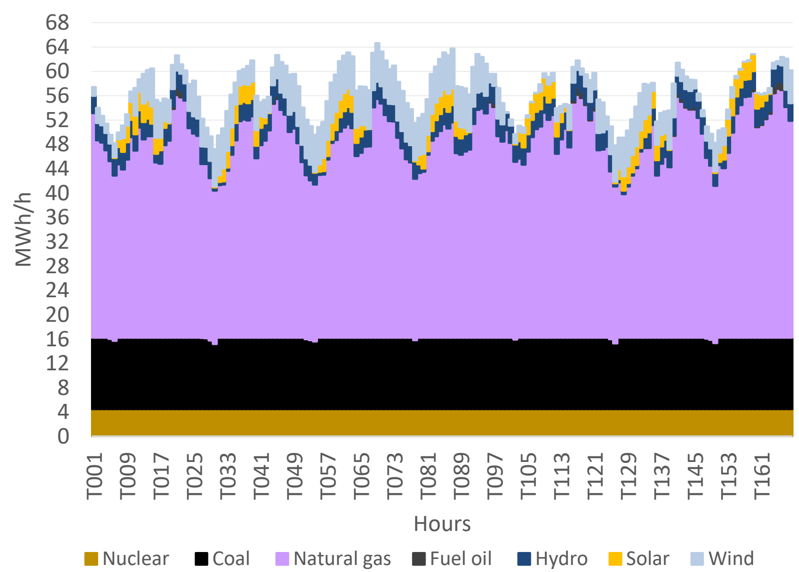
- **UnitComm**: Enables start-up costs, minimum generation and fixed fuel use and online O&M costs
- **UnitCmin**: Enable minimum up and down time
- **UnitCramp**: Enable ramp up and down rates
- **UnitCRMIP**: Run with relaxed mixed integer programming.

The Balmorel model is usually a linear programming model. When unit commitment added, the optimisation becomes a mixed integer problem (introduction of integer variables: a unit can be either on or off). Using relaxed mixed integer programming, the integrality constraint is relaxed again to a linear constraint.

It is important to note that the unit commitment problem is very time consuming due to the loss of convexity. It is therefore recommended to use unit commitment only when:

- Operational details are important
- Using an hourly time resolution
- Assessing power plant flexibility
- Not optimising investments

Generation profile with unit commitment run



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Technology definitions

The definition of all technologies available in the Balmorel model happens in the Parameter *GDATA*. This parameters allows the used to define the most important characteristics related to the operation, the economy, the investment timeframe, storage definition and unit commitment of the technology. A list of the different technology settings (one dimensional set *GDATATYPE*) is shown in the right.

The *GDATA* parameter defines both technologies for which the capacities are defined exogenously in the model (in the *GKFX* parameter) as well as the "technology catalogue" (defined in *ALLOWED_INV* or *ALLOWEDINV_STAND.*)

GDTYPE

GDTYPE number	Description
1	Condensing thermal technology
2	Backpressure thermal technology
3	Extraction thermal technology
4	Heat only
5	Heat pumps
6	Short-term heat storage
7	Short-term electricity storage
8	Hydro with reservoir
9	Hydro run-of-rive
10	Wind power
11	Solar PV
21	Solar heat
22	Wave power
23	Seasonal heat storage
24	Seasonal electricity storage

* Electric for condensing and extraction units, thermal for backpressure, heat-only boilers, generation for storages

GDATATYPE settings

GDATATYPE name	Description
Operation of the technology	
GDTYPE	Technology type selection (#, see table left)
GDFUEL	Fuel used by technology (#, FDNB in the FDATA parameter)
GDFE	Fuel efficiency*
GDCV	C_v value
GDCB	C_b value
Economy	
GDINVCOST0	Investment costs (Million money/MW)
GDOMFCOST0	Fixed O&M costs (Thousand money/MW)
GDOMVCOST0	Variable O&M costs (money/MWh*)
Investment timeframe	
GDKVARIABL	1 if the technology is an investment option, 0 if not
GDFROMYEAR	First year the technology can be invested in by the model
GDLASTYEAR	First year the technology can no longer be invested
GDLIFETIME	Lifetime of the technology if invested in by the model
Storage	
GDSTOHLOAD	Hours needed to fully load the storage (MWh_{vol}/MW_{load})
GDSTOHUNLD	Hours needed to fully unload the storage (MWh_{vol}/MW_{unload})
GDSTOLOSS	Stationay loss in storages (% of stored energy per timestep)
Unit commitment	
GDUC	1 if the technology will use unit commitment
GDUCUNITSIZE	Unit size on which the unit commitment will apply
GDUCUCOST	Start-up costs ($money/MW_{cap}$)
GDUCGMIN	Minimum generation (% of Mw_{cap})
GDUCCOST0	Online O&M cost ($money/MW_{cap}$)
GDUCF0	Fixed fuel use (% of fuel use at full capacity)
GDUCUTMIN/GDUCDTMIN	Minimum up- and down time (hours)
GDUCRAMPU/GDUCRAMPD	Ramp up and down time (% of capacity per hour)

MARKET AND REGULATION

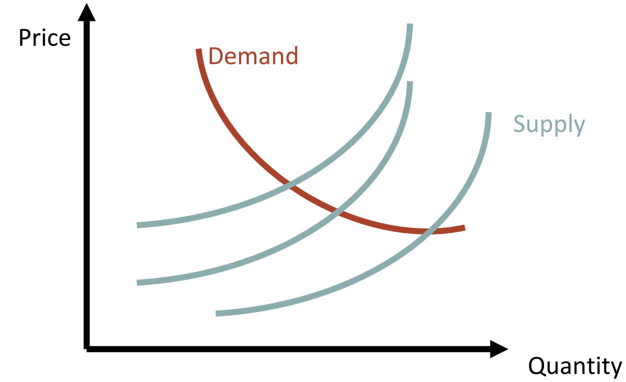
Electricity price

In the Balmorel model, an electricity price is calculated for each region and each time segment of the year. This price represents the electricity producers' marginal cost of generation (including fuel costs, fuel and emission taxes, and operation and maintenance costs) of the marginal unit of production. This value is in equilibrium with the marginal willingness to pay for wholesale power. This means that all units operating will at a minimum recover their short term marginal costs. In an investment run, when necessary to make new investments (part of) the long term marginal cost can also be reflected in the electricity prices. This is especially the case when no flexible demand is assumed.

The traditional illustration of this is shown on the right, however, it is important to note that there is an implicit calculation of all relevant opportunity values, e.g. storage options, electricity heat relationships, reservoir.

Electricity demand productions

… considering fuel prices, subsidies or taxes, O&M costs, subsidies, losses and costs in transmission and distribution,…



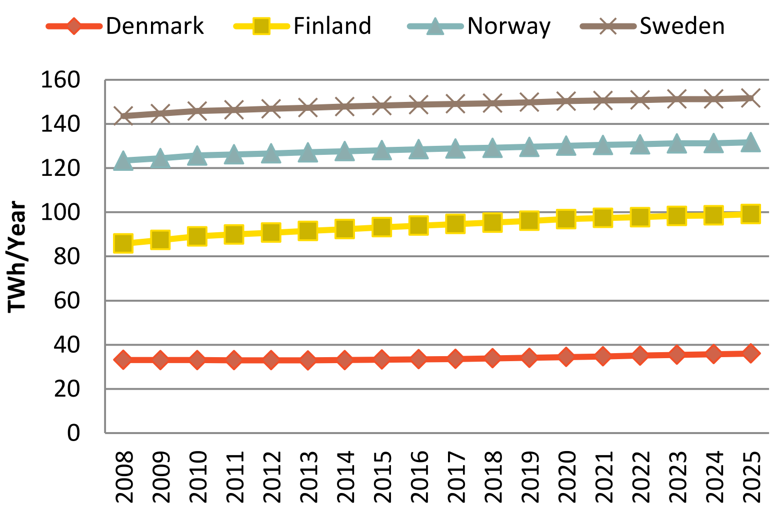
Electricity consumption

The consumption varies depending on geography and time given in the parameter *DE*. Additionally, the time variation over hours of the year is given by the parameter *DE_VAR_T*. From this the *nominal demand* is calculated for each time-step in each region.

Demand may deviate from the nominal demand if the option for price responsive demand is applied. This is handled by defining either relative or absolute steps the price can move in relation to a nominal price schedule. These steps are defined in the parameter *DEF_STEPS*.

On the right is shown applied assumptions of the development of annual demand in the Nordic countries. Behind these are hourly values.

Example of annual electricity consumption



Taxes and subsidies

Taxes and subsidies are subject to continuous intervention and revision by governments and regulators. Depending on the political decisions in an area, different taxes and subsidies are presented.

In the core model emissions of CO_2, SO_2 and NOx can be capped or taxed on a country level. Emissions can naturally be calculated and if a cap is a binding constraint, the shadow price (representing the necessary tax to achieve the same emissions) can be extracted.

Taxes on consumption of electricity and heating is also represented. Note that these only impact the endogenous operations and investments if the consumption is modelled as price responsive.

Balmorel can asses the impact of policies on climate gas emissions

Numerous policies to curb emissions which can be modelled

http://multimedia.pol.dk/archive/00402/Skorstene_402369x.jpg

Taxes on fuels, generations and other policy aspects

Taxes can be placed on fuel inputs (*TAX_F* and *TAX_GF*) or production outputs (*TAX_GE* and *TAX_GH*) on particular units in particular areas. Taxes and subsidies can also be placed on investments into new capacity. Subsidies are generally represented as negative taxes.

In addition to the core regulation functionality there are numerous add-on modules which have been developed over time which permit inclusion of various policy measures, e.g.

- International limits on emissions
- Renewable energy portfolio requirements
- Green certificate schemes

Making additional add-on modules to reflect policy is not necessarily a big task, due to the flexibility of the modelling language.

Policy requirement

In many scenario analyses it will be interesting to look at implication of existing of potential policies. Balmorel has a policy-add on which allows to model many different types of policy requirements which are predefined in a one dimensional set called POLICYTYPE:

- **ERENEWSHARE**: Renewable power generation must be a certain share of total power demand. Fuels are determined to be (partly) renewable or not in the FUELS parameters (FDRE).
- **EHRENEWSHARE**: Renewable power and heat generation must be a certain share of total power and heat demand. Fuels are determined to be (partly) renewable or not in the FUELS parameters (FDRE).
- **MINPROD/MAXPROD/EQPROD**: The sum of the annual power generation from selected units has to be minimum/maximum/equal to a certain amount (MWh)
- **MINCAP/MAXCAP/EQCAP**: the sum of the power capacity of selected units has to be minimum/maximum/equal to a certain amount (MW)
- **MINFUELUSE/MAXFUELUSE/EQFUELUSE**: The sum of the annual fuel use from selected units has to be minimum/maximum/equal to a certain amount (GJ)
- **MAXCO2:** The sum of the CO_2 emissions from selected units has to maximum a certain amount (Mtonne)
- **MINFLH/MAXFLH:** the full load hours of selected units has to be minimum/maximum a certain amount (hours)

Certain policies or resource restrictions can be implemented without using the policy add-on. The following parameters can be used: TAX_GE, TAX_GF, FKPOT, GEQF, GMAXF, GMINF, M_POL, NOINVF. These parameters are more straight-forward but also more limited in their use. More information can be found in the list of parameters in the *Data Input* section.

How to set-up a policy

For setting up a new policy, a couple of steps need to be followed:

1. Name the policy. In the one dimensional set POLICY, include the name of the new policy. (e.g. Windpolicy)
2. Define the policy by connecting it to the right POLICYTYPE (as listed to the left) in the two dimensional set POLTYP (e.g. POLTYP: Windpolicy .MINCAP)
3. Name the geography where the policy applies. In the one dimensional set POLAREA, include the name of the geography (e.g. Threeregions)
4. Define the geography by connecting it to countries, regions or areas in two dimensional set POLAREAGEO (e.g. POLAREAGEO: Threeregions.(Highregion,Goodregion,Richregion)
5. Define to which units the policy applies in two dimensional set POLTECH (e.g. Windpolicy.Windtechnology)
6. Or define for which fuels the policy applies in the two dimensional set POLFUELTECH (e.g. Windpolicy.Wind)
7. Give the value for the policy in the correct unit in the parameter POLREQ for the years it should be applied and in the policy geography defined earlier (e.g 2040.Threeregions.Windpolicy 50000)

MODEL SETUP

Description of the set-up and running of model

General Algebraic Modeling System - GAMS

The General Algebraic Modeling System is a commercial product developed by the GAMS cooperation (www.gams.com).

- Key idea 1: separate model and solver
- Key idea 2: separate model structure and data
- Not energy specific – can model almost anything
- Primarily developed for optimisation models
- Solvers: commercial and free/open source

The basic components and structure of any GAMS program are:

- *Sets* – groups of entities (labels), subsets of other sets, relationships between elements of different sets (intersections)
- *Parameters* – data (numbers) usually defined over, or indexed by, a number of sets. Alternatively given as *Tables*.
- *Variables* – endogenous variables whose values are defined as solutions to the model run. These are the unknowns determined by optimisation.
- *Equations* – relationships which must hold between variables and parameters.

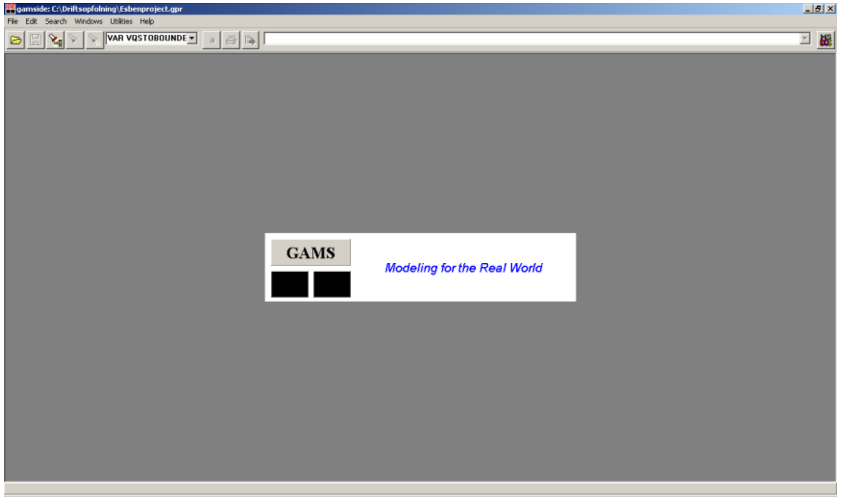
A model is formulated generically over sets, e.g. one writes one equation and the domain, and it will hold for any number of instances.

Modelling language and flexibility

Applying a high level modeling language (GAMS) and standard model classes (e.g. LP, MIP) implies flexibility:

- No formal limit on amount of data (e.g. number of countries, number of plants, number of fuels)
- Flexible time resolution – e.g., can simulate on annual or hourly basis, or something in between
- Transparency of functionality – no hidden assumptions
- Possibility to extend model to adapt to specific needs
- Rigorous derivations of prices

GAMS Integrated Development Environment (GAMS IDE)



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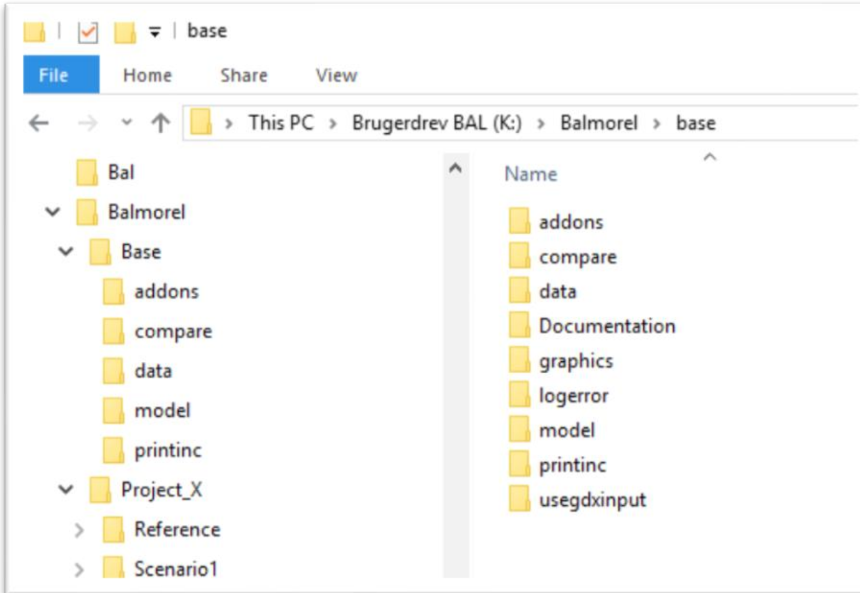
Model structure Base – files and locations

File structure of base folder

The base folder is the folder where all the important functionality of the model is located, as well as where the data files with 'main assumptions' should be placed.

- The main file is *Balmorel.gms* located in *\base\model*. This file collects all the other files which have been chosen to be included. It is from this file the Balmorel model can be executed. This file defines the sets, variables and equations, which are placed in *\base\model*.
- The set-up of options for a specific run can be done in the *Balopt.opt* file, also found in *\base\model*.
- All data files (i.e. the parameters) are located in the *\base\data* folder.
- Control of output is handled in *\base\printinc*.
- The *\base\printout* folder is the destination folder for the main text based output of results from the simulation.
- The *\base\compare* directory contains additional output files for the economic module. These are formatted for import to Excel.
- The *\base\logerror* directory contains two logs which can be used for debugging. The file *logfile.out* contains debugging information from the GAMS system and solver. This file is completely oblivious to the fact that Balmorel is an energy sector model. The file *errors.out* contains minor checks on input data and on the solution returned. Errors in this file take account for the energy subject matter.
- Add-ons can contain extra sets, parameters, equations and variables with a specific add-on functionality in mind. These extra files are placed in *\base\addons*.

Folder structure



Structure of base/model

- balmorel.gms (the GMS file)
  - Definition of parameters and variables
  - Formulation of the objective function
  - Formulation of constraints
  - Definition of the models (balbase1, balbase2, balbase3)
- bb123.sim
  - Simulation file, sets specific conditions for model variations (balbase1, balbase2, balbase3)
- balopt.opt
  - Options for the current simulation (high level decisions)
- A number of input files

Structure of the GAMS model

The structure of any GAMS model follows the formula:

- Sets - definitions and initialisation
- Parameters - definitions and initialisation
- Variables - definitions
- Equations - definitions and symbolic expression of relationships between variables and data
- Bounds - bounds are assigned on variable domains
- Solve - the model is generated and solved

In Balmorel, a simulation structure is added as a loop over each year in the simulation, where bounds and internal parameters are updated to the current simulation year, possibly taking account of results from the previous year (investments).

Constraints/equations

The some of the main types of constraints of the model are generically described below:

- Electricity and heat supply and consumption should balance at all times
- Generation technologies' electricity/heat operating area should be complied with
- Production of dispatchable and non-dispatchable units (including thermal units, hydro power, wind, solar etc.) should not exceed capacity or availability (e.g. for wind)
- Transmission is limited to capacity
- Storage balances
- Resource constraints on capacity and/or energy.
- Policy restrictions should be adhered to
- …

Objective value

Balmorel is a linear programming model, seeking to **minimize** the objective value, some terms of the sum are listed here:

Objective =

Fuel cost
+ O&M costs (fixed and variable)
+ Transmission costs (losses)
+ Emission taxes
+ Fuel/energy taxes
+ Capital costs (new units)
– Subsidies
– consumer utility in relation to nominal utility of consumption.

Simplified linear programming problem

Minimize	$Z = \sum_{t \in T} \sum_{j \in J} a_{jt} f_{jt}$		Objective function
Subject to	$\sum_{j \in J} p_{jt} = d_t$	$\forall t \in T$	Structural constraints
	$p_{jt} \leq p_j^{max}$	$\forall j \in J \ \& \ \forall t \in T$	
	$f_{jt} = \frac{p_{jt}}{\epsilon_j}$	$\forall j \in J \ \& \ \forall t \in T$	
	$p_{jt} \leq 0$ $\geq$	$\forall j \in J \ \& \ \forall t \in T$	Non-negativity constraint

j: area, t: timestep, a: fuel costs (money/unit of consumption), f: fuel consumption, p: power production, p^{max}: power capacity, ϵ: fuel efficiency

The simplified linear programming problem minimizes the fuel costs while keeping the following constrains:

- Production meets demand
- Production does not exceed capacity
- Fuel consumption is linked to production by the fuel efficiency
- Production is a non-negative variable.

Extensive Balmorel linear programming scheme

Nomenclature:

Indexes

- g: technology
- c: cost
- e: electricity
- h: heat
- f: fuel
- t: time
- x: transmission line
- a: areas
- w: emission

Coefficients/relationships

- a: annual cap. Recovery
- η: marginal efficiency
- c: extraction coeff.
- c^e: back pressure coeff.
- k: idle fuel consumption
- κ: nominal unit size
- r: variable resource
- K: capacity
- m: minimum unit load
- loss: loss factor
- A: annual resource
- T: target
- W: emission factor

Variables (endogenous)

- G: generation (MW)
- D: demand (MW)
- X: transmission (MW)
- I: Investments (MW)
- S: start units (#)
- Dn: shutdown (#)
- O: Units online (#)
- L: Storage level (MWh)
- Z: System costs

Input data:
Electricity and DH-generation
Energy demand projections
Resource characteristics
Resource limitations
Transmission system

↓

Loop: $Y=Y_0$ to Y_N

↓

Solve: least-cost optimal capacity expansion, unit commitment and economic dispatch problem:

$$\min Z_y = \sum_{g,t} c^e_{g,t} \cdot G^e_{g,t} + \sum_{g,t} c^h_{g,t} \cdot G^h_{g,t} + \sum_{g,f,t} c^f_{g,t} \cdot F^f_{g,t} + \sum_{g} (a \cdot c^I_g + c^{fix}_g) I_g + \sum_{x} a \cdot c^I_x \cdot I_x + \sum_{g,t} c^s_{g,t} \cdot S_{g,t} + \sum_{g,t} c^o_{g,t} \cdot O_{g,t}$$

Cost: el. gen | *Cost: heat gen* | *Cost: fuel cons* | *Cost: new gen inv.* | *Cost: new trans inv.* | *Cost: unit start* | *Cost: unit is online*

Subject to:

Supply and demand balance:

Electricity:

$$\textstyle\sum_g G^e_{g,t} + \sum_x (1 - lossx) X^{Import}_{x,t} = \sum_x X^{Export}_{x,t} + D^e_t$$

Heat:

$$\sum_g G^h_{g,t} = D^h_t$$

Fuel:

$$F^f_{g,t} = G^e_{g,t}/\eta^e_g + G^h_{g,t}/\eta^h_g + k^f_g \cdot \kappa^f_g \cdot O^f_{g,t}$$

Technology constraints (selected):

Extraction units:

$$G^e_{g,t} - c^v_g \cdot G^h_{g,t} \le K^e_g$$

$$G^e_{g,t} \ge c^b_g \cdot G^h_{g,t}$$

Electric boilers/heat pumps

$$G^h_{g,t} = D^e_{g,t}/\eta_h$$

Variable RE

$$G_{g,t} \le r^f_t \cdot (K_g + I_g)$$

Hydro w. storage

$$L_{g,t+1} = L_g, t + r^{HY}_t \cdot (K_g + I_g) - G^e_{g,t}$$

Transmission constraints:

$$X_{x,t} \le K^x + I^x$$

Unit commitment:

Commitment logic

$$S_{g,t} - Dn_{g,t} = O_{g,t} - O_{g,t-1}$$

Min. fuel input

$$F^f_{g,t} \ge m_g \cdot \kappa^f_g \cdot O_{g,t}$$

Max fuel input

$$F^f_{g,t} \le \kappa^f_g \cdot O_{g,t}$$

Resource constraints:

By fuel

$$\sum_{g\sim f,t} F^f_{g,t} \le A_f$$

By capacity

$$\sum_{g\sim f} (K_g + I_g) \le A_f$$

Policy targets:

Capacity by fuel

$$\sum_{g\sim f} (K_g + I_g) \ge T^K_f$$

Emission cap

$$\sum_{g,t} W^f_w \cdot F^f_{g,t} \le T_w$$

Dispatch rules:

Full load hour requirement

$$\sum_t G^e_{g,t} \ge FLH_g \cdot (K_g + I_g)$$

↓

Update capacities
- Generation
- Transmission

(→ back to Loop)

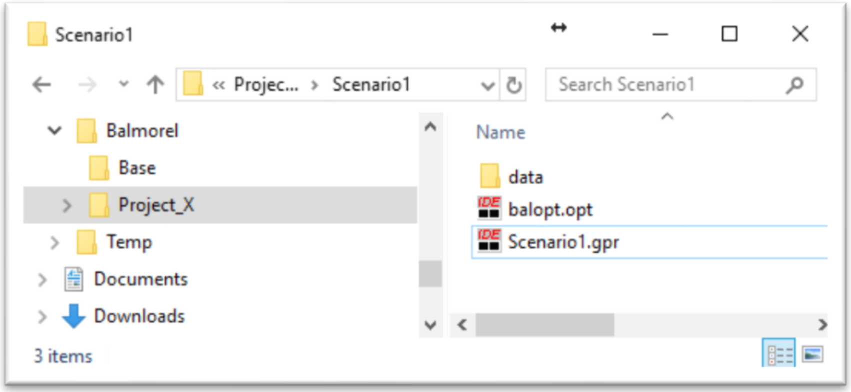
Final results

Technical details

Most practical applications require the generation of several scenarios. Some scenarios consist of simple changes in relation to a baseline, such as single price, an alternative time-series or a change of a capacity of a unit or transmission line. Other scenarios are more complex and require alternative model code and numerous data alterations. In principle there is no restriction how scenarios are created and there is not a single way of handling scenarios.

Scenarios can be thought of as alterations in relation to the core data (base). When copying an existing file in a scenario case, the model prioritizes files in the scenario catalogue and disregards the corresponding files in the base folder.

Scenario folder structure



How to create and run a new scenario

1. Create a **Project folder** (e.g. *Project_X*) besides base.
2. In the Project folder, create a **Reference folder** (R*eference*).
3. Also in the Project folder, create a **Scenario folder** (e.g. *Scenario1*).
4. The Scenario folder should contain a *balopt.opt* file.
5. Create a data folder in both the Reference and Scenario folders, include any data-files in which changes should be made compared to the version of the file in the base folder. Project specific data should be included in the *Reference/data* folder, while scenario specific changes should be placed into *Scenario/data* folder.
6. Open GAMS IDE
7. Create a project (.gpr file) in the Scenario folder (e.g. *Scenario1.gpr*) by clicking *File/Project/New project.*
8. Open the *Balmorel.gms* file from the *base/model* folder
9. Write 'cerr=1' in the command line. (This will cause the run to stop in case compilation errors were found)
10. Press F9 or the run button 

Batch file runs

Using the GAMS IDE interface is very useful when starting to use the Balmorel model or for error solving. One disadvantage of the interface, however, is that it can only execute one simulation at a time. Running Balmorel using batch files does not have this limitation.

Place the executable GenerateGamsBatFiles.exe in the **Project folder** and double click it. The file will create a batch file for each **Scenario folder** in the project that contains a balopt file. Running these batch files will run the respective scenario. Two additional files will be created:

- **AllParallel:** runs all scenarios in parallel (open with text editor to time between runs – in seconds)
- **AllSequential:** runs all scenarios in sequence (open with text editor to adjust order)

Importance of folder structure and hierarchy

When the model loads information (input data, additional equations, transfer files etc.,) it will try to include data from several location in a specific order:

- First, it will look at locations "closest" to the location of the project(.gpr) file, where scenarios specific data should be placed
- If the specific file is not found there, the model will look at the next location in the hierarchy. (Illustrated on the right).

This hierarchy makes it convenient to create new scenarios with just a few changes compared to a base scenario. One does not need to copy all the input files to each new scenario, thereby potentially losing track of changes made in some of the scenario folder but not in others and losing overview. In stead one can simply make a new version of the input file that differs from the main assumptions and the model will use base assumptions for the remaining input.

Model hierarchy

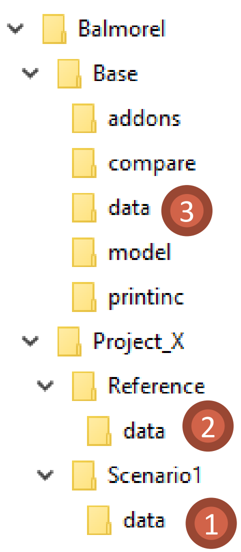
When loading information, the model will first look at files in the following order:

1. Scenario folder (where project file is located)
2. Firstaddreffolder (optional, set in Balopt.opt)
3. Addreffolder (optional, set in Balopt.opt)
4. Reference folder (in the current project folder)
5. Base folder
6. Specific path given when loading the data

In all these locations, if there exists a data folder, the model will first look there and after it will look at files in the folder itself.

The folder structure below shows where the model will look when running Scenario1 (no Firstaddreffolder/addreffolder given).

Example of order of reading input files



Balopt.opt hierarchy

Where for other information, the model will stop looking through the hierarchy when it finds the closest version of the file it is looking for, in case of the Balopt.opt file, the model will read all files in the hierarchy tree.

It will read the content of the last version in the tree first, then it will move up on the tree (from #6 to #1 in the list above). Whenever new data is read, it will overwrite the previous version.

This way, it is not necessary to define all settings in the balop.opt file and it is enough to only write the settings which are different from the versions of the balopt.opt file further down the hierarchy tree.

Model alternatives

There are three model variations in the core model:

- Balbase 1 (**BB1**): Optimizes integrated operations for one year.
- Balbase 2 (**BB2**): Optimizes integrated operations and capacity expansion for one year. Will also be called **investment run** in this manual.
- Balbase 3 (**BB3**): Optimizes integrated operations each season iteratively (per week). Boundary conditions needed for each season with respect to seasonal hydro and other annual balances. Will also called **hourly run** in this manual.

The decision of which model type will be run is made in *Balopt.opt*.

The BB2 and BB1 model runs can generate output files which can then later be used as input files for second runs. These files can contain information on investments made in a BB2 run, annual allocation of hydro generation, shadow prices of policy constraints etc. see section on *Transfer of files between runs*.

Overview of different model alternatives

	BB1	BB2	BB3
Optimises	A full year	A full year	Week by week
Timeaggregation	Recommended	Recommended	Not possible
Investments	No	Yes	No
Allocation of hydro/storage generation	Annually optimized	Annually optimized	Weekly optimized + uses input from BB1/BB2

Types of files

Main script: Balmorel.gms (Main code)

Further modelling scripts: Other files in base/model (.gms)

Simulation file: BB123.sim

Option file: Balopt.opt (decide on options)

Include files: Input data files (.inc and .gdx files)

Transfer files: Files which are both input and output files (.gdx)

Output files: "name".gdx: all input and results gathered in tables (scenario folder/Output/)

Results files: INPUT.gdx, OUTPUT.gdx or "year".gdx all input gathered, all output (not created during the yearly loop) all yearly results gathered (this data is merged to the output file and is located in Scenario folder/Results)

GDX file

GAMS Data eXchange (GDX) file format is a particular format providing basic functionalities for exchanging data with GAMS, normally used to write inputs or read outputs to and from the GAMS modelling environment. It stores the values of one or more GAMS symbols such as sets, parameters variables and equations.

		GDTYPE	GDFUEL	GDCV	GDCB	GDFE	GDINVCOST0	GDOMVCOST0
1INPUT	Biomass_20_34	1	13			0,35	2,445875	
	Biomass_35_50	1	13			0,35	2,359961	
	Straw_20_34	1	11			0,31	2,863813	
	Straw_35_50	1	11			0,31	2,863813	
	Wood_20_34	1	20			0,31	2,863813	
	Wood_35_50	1	20			0,31	2,863813	
	Bagasse_20_34	1	21			0,31	2,863813	
	Bagasse_35_50	1	21			0,31	2,863813	
	Coal_CCS_20_34	1	22			0,34	3,563658	2,14786
	Coal_CCS_35_50	1	22			0,35	2,911245	2,237354
	Coal_sub_20_50	1	3			0,39	1,659222	2,14786
	Coal_super_20_50	1	3			0,43	1,979611	2,237354
	CCGT_20_34	1	2			0,6	0,783074	2,416342
	CCGT_35_50	1	2			0,62	0,783074	2,416342

Balopt file

The balopt.opt file is used to define the high level set-up for the the scenario. Each scenario folder should have a balopt file. In the folder Base/model, the “mother” balopt file is located. Here all the different options to set should be illustrated.

The balopt file contains a number of **global parameters** which should be set to the chosen value by using the following line of code: `$SetGlobal ‘Global_name’ ‘parameter value’`

As an example: `$SetGlobal ProjectID Project_X`

would set the project name of the scenario to ‘Project_X.’

Practical tips:

- A list of the most important global parameters and their description is found on the right.
- Some global parameters can have several values, in that case they should be separated by commas. An exception is the *Geographydata* global parameter, where different values should be separated by spaces.
- Sometimes it makes sense to set a global parameter to a range of values. In this case the ‘*’ symbol should be used. For example: `$SetGlobal Simulatedtimesteps T001*T168`, sets the timesteps used in the current simulation to all values ranging *from* T001 *to* T168.
- Make sure never to set more than one Balbase to ‘yes’, as only one kind of model simulation can be run at a time.
- When only one correct value is possible/recommended it is indicated between brackets.
- When a global parameter should not be activated (not be set to ‘yes’), it does not have to be mentioned at all. Setting it to ‘no’ or leaving it empty works as well.

Most important global parameters

Global_name	Description
ProjectID	Name of the project
CaseID	Name of the scenario
Coredatefolder	Set base folder (‘Base’)
Referencefolder	Set reference folder for the project (‘Reference’)
Addreffolder/Addfirstreffolder	Add additional reference folders
BB1	Set Balbase1 (‘yes’)
BB2	Set Balbase2 (‘yes’)
BB3	Set Balbase3 (‘yes’)
Simulatedyears	Years in simulation
Simulatedweeks	Seasons in simulation
Simulatedtimesteps	Timesteps in simulation
Simulatedcountries	Names of countries in simulations
Geographydata	Suffixes for which data should be loaded
Omoney	Currency conversion factor input to output currency
Timeaggr	Use time aggregation (‘yes’)
Investfrom	First year generation investments are allowed
Xinvestfrom	First year transmission investments are allowed
Decomfrom	First year generation decommissioning is allowed
Policy	Enable the policy add-on (‘yes’)
Makeinvest/MakeinvestBB2	Generate output files on invested capacity (‘yes’)
Makewater	Generate output files on hydro allocation (‘yes’)
Addinvest/AddinvestBB2	Load output files on invested capacity (‘yes’)
Addpolicy	Load output files on policy shadowvalues (‘yes’)
UnitComm/UnitCmin/UnitCramp	Use unit commitment (UC) parameters (‘yes’)
UnitRMIP	Use relaxed mixed integer programming (‘yes’)
MakeSQL	Send output generated to the database (‘yes’)

Why use transfer files

Certain runs can produce **output files** that can be used as **input files** by other runs. These special **transfer files** (extension .gdx) are created/loaded in the printout folder.

In many cases it can be useful to first run a BB2 run which
- Can invest in generation and transmission capacity
- Can decommission exogenous capacity
- Optimises a whole year at once and can therefore allocate hydro generation, optimise the use of seasonal storage and implement restrictions and policies on annual values (e.g. maximum annual CO_2 emission)
- Uses time-aggregation

Subsequently a BB3 run can be made, for a more detailed look at the hourly (non time-aggregated) dispatch. This BB3 run cannot optimise capacities and looks only at one week at a time.

It can, however, load information from the BB2 run about
- Investments/decommissioning in capacity
- Seasonality of hydro generation
- Seasonality of seasonal storage
- Shadow values/prices of policies and resource restrictions

Thereby combining the accuracy of an hourly run and the investments/full-year overview of the investment run.

Practical tips:
- In other cases it can be useful to make a BB2 + BB1 run/ a BB1 + BB3 run/a BB2 + another BB2 run (use MAKEINVESTBB2/ADDINVESTBB2)
- When using the seasonality of hydro in the hourly run, you can either fix the amount of water allocated to each season or the value of water (hydro) in each season by setting WATERVAL to no or yes respectively
- A simple definition of shadow value or shadow price is the economic benefit in case the restriction was one unit less restrictive (e.g. you can use 1GJ more of a restricted fuel)
- Make sure your second run reads the right files by remembering the folder hierarchy!

Overview of important transfer files

Parameter name	Description
Created by MAKEINVEST, loaded with ADDINVEST	
GVKGN	Endogenous generation capacity for each year
GVDECOM	Decommissioned gen. capacity for each year
GKVACC	Accumulated endogenous gen. capacity
GKVACCDECOM	Accumulated endogenous and decommissioned gen. capacity
XKACC	Accumulated endogenous transmission capacity
Created by MAKEINVESTBB2, loaded with ADDINVESTBB2	
GKVACCDECOMBB2	Accumulated endogenous and decommissioned gen. capacity for BB2 run
Created by MAKEWATER, loaded with ADDWATER	
HYFXRW	Hydro allocation per season (used when WATERVAL not ‘yes’)
WATERVAL	Value of water (hydro) per season (used when WATERVAL ‘yes’)
Created by POLICIES + ADDPOLICIES not ‘yes’, loaded with POLICIES + ADDPOLICIES	
POLICIES_ SHADOWVALUES	Shadow values of policies
Created by FUELVAL + BB3 not ‘yes’, loaded with FUELVAL + BB3	
FUELVAL	Shadow price per season for fuels with fuel restriction
Created by BB3 not ‘yes’, loaded with BB3	
STOVAL	Storage content in the end and the beginning of the season

Time, a fundamental modelling concept

The representation of the passage of time is fundamental to any dynamic power system model. The Balmorel model in it's core form adopts two parallel concepts for this representation. For each of them, three layers of time is represented (years, seasons, time steps).

It is distinguished between:

- Data time: time by which input data is given
- Simulation time: time by which the simulation is run

Data time

Time dependent data input is for different data given either by *year*, or by *week* and *hour* of the week. To maintain simplicity these data are limited to 52 weeks of 168 hours (e.g. 8736 hours), Additionally, it is a useful convention to always correct hourly data so that the year starts Monday 00:00-01:00.

Parameters for data are given with indexes which are set elements of the set of years *YYY*, weeks *SSS*, and hours *TTT*.

Simulation time

Simulation time is the space defined over a subset of the three sets of years, seasons and time steps. Years are *Y*, seasons are *S* and time steps are *T*. Whichever simulation time is used, the model will make sure the to assign a weight to each time segment so that the weighted time segments add up to 8760 hours (normal full year)

Hourly simulations

Hourly simulations (BB3 runs) have a different execution schedule than normal annual simulations which are aggregated. In hourly simulation time each hour of the year (or of selected weeks) is represented. Since the model would be too big to solve for all hours of the year in one simulation (for large systems), one week at a time is run (often in parallel).

Aggregation of time

Separation between data and simulation time is useful as one is able to run simulations on a smaller number of time segments or with a shorter time horizon than one has built up a data set for, in order to save on model run-time. Another advantage is that the model is able to have data stored in one resolution and can then aggregate to fit another resolution.

When running with time aggregation (timeaggr set to 'yes' in balopt), aggregation can take place in two levels:

- **Aggregation of seasons**: when running with less than 52 weeks (defined as *Simulatedweeks* in balopt.opt), several weeks will be grouped and averaged (e.g. when running with 13 weeks, every 4 weeks will be averaged)
- **Aggregation of time steps**: numerous principles for time aggregation are applied. A common approach is to aggregate hours which under normal circumstances would be expected to display similar characteristics, e.g. level of electricity demand. The user can indicate a desired scheme for aggregating hours into time steps in the *timeaggr.inc* file in the *base/model* folder. The number of timesteps (defined as *Simulatedtimesteps* in balopt.opt), has to match the scheme set-up in the *timeaggr.inc.*

Timeaggr.inc

- **TABLE TINDAY(T,DAY):** defines whether that time step should be counted in that day of the week.
- **TABLE T2HOURS24(T,HOURS24):** defines whether the time step should be counted during that hour of the day.

An example can be seen on the next slide.

EXAMPLE OF TIME AGGREGATION

Example of the two timeaggregation tables

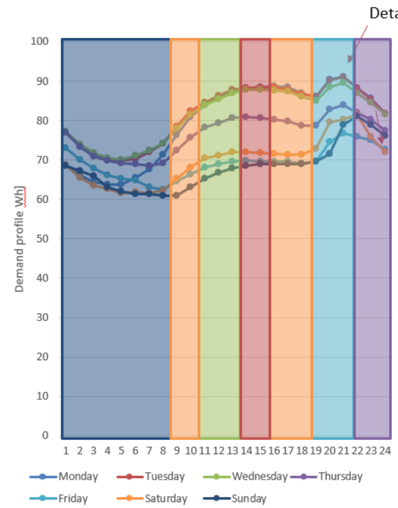
		T001	T002	T003	T004	T005	T006	T007	T008	T009	T010
1	Monday	1	1	1	1	1					1
2	Tuesday	1	1	1	1	1					1
3	Wednesday	1	1	1	1	1					1
4	Thursday	1	1	1	1	1					1
5	Friday	1	1	1	1	1					1
6	Saturday						1	1	1	1	1
7	Sunday						1	1	1	1	1

		T001	T002	T003	T004	T005	T006	T007	T008	T009	T010
1	1st hour										1
2	2nd hour										1
3	3rd hour										1
4	4th hour										1
5	5th hour										1
6	6th hour										1
7	7th hour										1
8	8th hour										1
9	9th hour	1					1				
10	10th hour	1					1				
11	11th hour		1				1				
12	12th hour		1				1				
13	13th hour		1					1			
14	14th hour			1				1			
15	15th hour			1				1			
16	16th hour	1					1				
17	17th hour	1					1				
18	18th hour	1					1				
19	19th hour				1				1		
20	20th hour				1				1		
21	21st hour				1				1		
22	22nd hour					1				1	
23	23rd hour					1				1	
24	24th hour					1				1	

The upper table represents **TINDAY** and the lower table represents **T2HOURS24.** For the time aggregation, the time step T001 will be an average value of all timesteps where a 1 is indicated (in this example Monday-Friday for the hours 9-10 and 16-18).

To the right, the reasoning behind a good time aggregation is shown. The time aggregation should be more detailed for peaks and can be less detailed for flat parts (nights/weekends) of the important variation profiles (mainly power demand and solar generation)

Time aggregation should consider demand



Weekdays:

- T001: 9-10 + 16-18
- T002: 11-13
- T003: 14-15
- T004: 19-21
- T005: 22-24

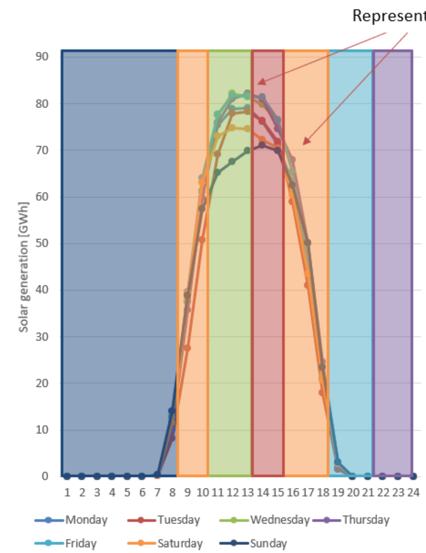
Weekend days

- T006: 9-12 + 16-18
- T007: 13-15
- T008: 19-21
- T009: 22-24

Night, all days:

- T010: 1-8

Time aggregation should consider variable generation (mainly solar)



Weekdays:

- T001: 9-10 + 16-18
- T002: 11-13
- T003: 14-15
- T004: 19-21
- T005: 22-24

Weekend days

- T006: 9-12 + 16-18
- T007: 13-15
- T008: 19-21
- T009: 22-24

Night, all days:

- T010: 1-8

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Errors in Balmorel

Balmorel is a highly flexible model, where functionality and data can easily be added. However, this high level of flexibility makes it also hard to oversee the many implications of a small change. As the model is open-source, there is no-one accountable for potential errors within the model. Therefore, it is useful to have some basic skills in error handling of the model.

There are three types of errors in the model:

- **Data-check errors**: These are errors are strictly related to logical and reasonable considerations and do not prevent the model compiling or solving the optimization problem
- **Compilation errors**: These are errors which prevent the model of setting up the optimization problem.
- **Execution errors**: These are errors which prevent the model of solving the optimization problem

Compilation errors

Compilation errors are the type of errors which prevent the model of compiling properly. When running from GAMS IDE, entering cerr=1, will result in a run-stop when 1 compilation error is found.

By double clicking, the red error message, the GAMS IDE will open the file with the error and put the cursor at (or close to) the error. Right underneath in black the kind of error is indicated. A very common error: `domain violation for element.` This means that the data entered is not allowed in the location it is used. Often this means it is not defined in the appropriate set. The GDXinput creator prevents this error to some degree.

```
-- ... ..\..\base\model\includeGeographyData.gms(18) 275 Mb
-- .... data\pol_data_MX.inc(10) 275 Mb 1 Error
** Error 170 in K:\Balmorel_MX\REO2018\7_Paris\data\pol_data_MX.inc
   Domain violation for element
-- ... includeGeographyData.gms(18) 275 Mb
-- .. ../../base/model/IncludeGeography.gms(15) 275 Mb
-- . ../../base/addons/policies/pol_include.inc(10) 275 Mb
-- balmorel.gms(1103) 275 Mb 1 Error
** Status: Compilation error(s)
-- Job balmorel.gms Stop 07/16/18 15:44:12 elapsed 0:00:29.380
xit code = 2
```

Data-check errors

Data-check errors are a special type of error in that they are not model-errors as seen from a GAMS point of view. These types of errors are coded in Balmorel in order to check input data and to prevent logical inconsistencies. Examples of these type of errors include:

- A demand profile is given in a region for which no annual demand is provided
- Wind power capacity is located in an area where there is no wind resource data available.
- Fuel prices for natural gas is zero an area with natural gas generation

These type of errors can be found in the file **Scenario folder**/logerror/Errors-*CaseID*.out. The data-check errors are above the line: `X errors were detected in the input data before simulation.`

Execution errors

Execution errors are the results of serious inconsistencies in the input data.

An example could be that the wind power capacity should be both above 20 GW and under 10 GW for the same region. Another example could be that the demand has to be supplied in an islanded region without generation capacity.

These type of errors would normally result in an infeasible solution. In the Balmorel model, however, for many constraints slack variables are used which (at a high cost for the objective function) allow the model to break the constraints causing the infeasibility.

These type of errors can also be found in the file **Scenario folder**/logerror/Errors-*CaseID*.out. The execution errors are below the line: `X/No errors were detected in the input data before simulation` and given for each year

Basic GAMS syntax

This manual is meant as a guide for operators of Balmorel and will not teach GAMS programming. Nevertheless, a minimum of basic coding can be useful when operating the model. Some basic syntax rules for GAMS are:

- Letter case and blanks have do not matter in GAMS
- Statements are terminated by a semicolon ‘;’
- $ in position 1 is an instruction to the pre-processor
- a ‘*’ in the beginning of the line, out-comments the entire line
- Assignments can be done using the ‘=‘ sign
- To assign quote specific indices, use single quotation marks ‘ ‘
- [term] $ ([condition]):
- Sum(([indices over which to sum]),[expression to sum])

Instruction to the pre-processor

Instruction	Description
$Setglobal [Name] [Value]	Global parameter that can be used to set different options. [value] can be left blank. A global parameter can be recalled by %[name]%
$include/$batinclude [filepath]	Used to include (read) a file, without/with hierarchy
$ifi [condition]	This rest of the line after the [condition] will only be executed if the [condition] is true.
$ontext [text] $offtext	All text between $ontext and $offtext will be ignored as comments.

Examples

Assignment of DE parameter:

```
DE(‘2030’,’Region1’) = 33000000;
DE(‘2030’,IR)$(CCCRRR(‘Country1’,IR)) = 33000000;
```

The first assignment set the parameter DE for the year 2030 and the region 1. The second assignment set DE for all regions in country1 in year 2030.

Use of global parameters

```
$Setglobal Newcode yes
$ifi %Newcode%=yes $include
‘..\..\base\addons\newcode\newcode.inc’;
```

The file newcode.inc will only be included when the value of the global parameter Newcode is ‘yes’

Summing over an hourly profile

```
Sumofprofile(RRR) =
sum((SSS,TTT),Hourlyprofile(RRR,SSS,TTT));
```

The parameter sumofprofile for each region on the simulation is set to the sum ofparameter hourlyprofile over all seasons and all timesteps.

Equations

Syntax for equations in GAMS:

- [Equation name]([equation indices])$([condition for which equation applies])..
- Is equal to: =E=
- Is less\less or equal than: =L= \ =LE=
- Is greater\greater or equal than: =G= \ =GE=

Example:

The equation QGFEQ for all the technology and area combinations in IAGK_Y (existing capacity) defines that for every area, technology, season and timestep, the variable VGF_T (fuel consumption) is equal to VGE_T (electricity production) divided by the efficiency of the technology.

```
QGFEQ(IA,G,IS3,T)$(IAGK_Y(IA,G))..
      VGF_T(IA,G,IS3,T)
   =E=
      VGE_T(IA,G,IS3,T)/GDATA(G,'GDFE')
```

GAMS support and documentation

- GAMS support:
  - support@gams.com
  - Very rapid response!

- GAMS user list:
  - http://www.gams.com/maillist/gams_l.htm
  - Very strong community of professionals and academics!
  - Monitored by GAMS developers: Steven Dirkse, Erwin Kalvelagen, others.
  - Monitored by GAMS contributors: Thomas Rutherford, Michael Ferris, Bruce McCarl
  - Monitored by solver developers: Arne Drud, ...

- GAMS manuals – available through the GAMS IDE (help)
  - GAMS Users Guide
  - Expanded GAMS Guide – Bruce McCarl
  - Solver manuals (CPLEX)
- GAMS model library:
  - http://www.gams.com/modlibs/
  - Many useful sample models from different fields (e.g. transport.gms)

DATA INPUT

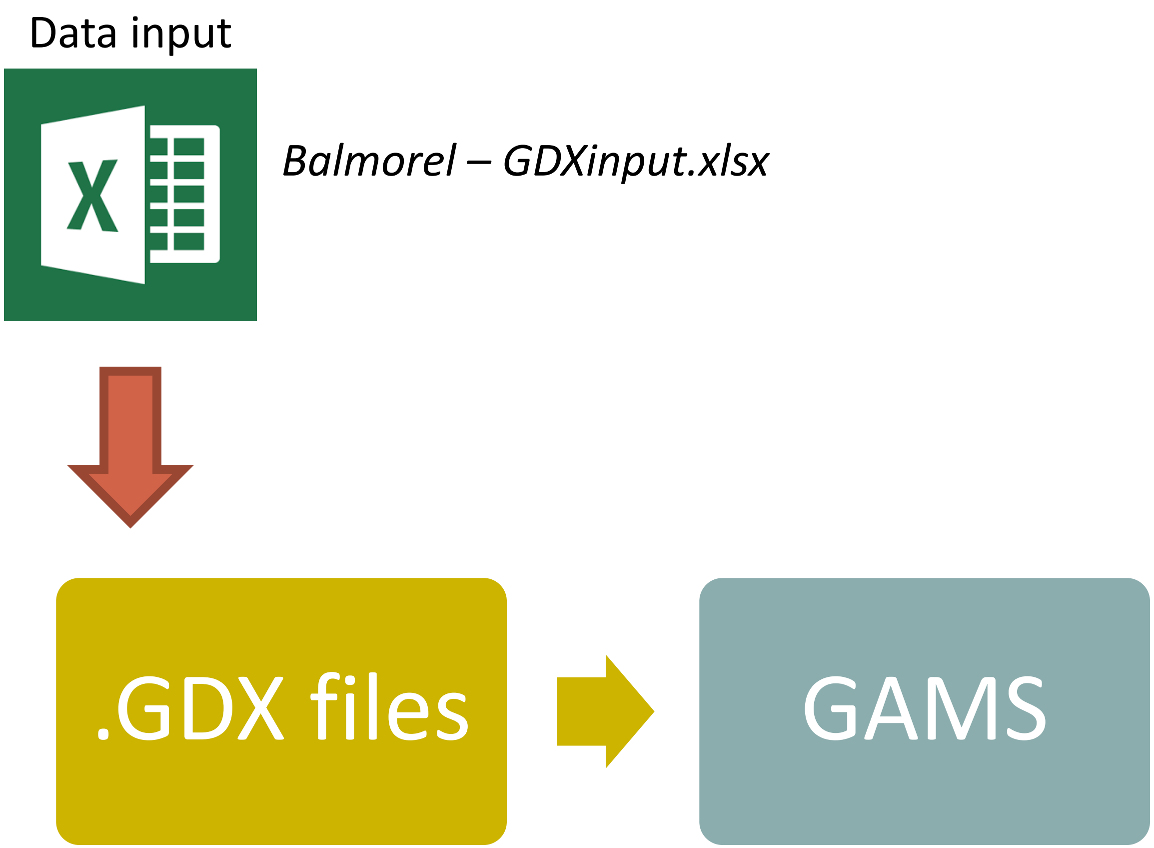
Understanding different types of data input required for the Balmorel model and how to generate them

Input of Balmorel

Ea Energy Analyses has developed a MS Excel sheet for input data to the Balmorel model named 'Balmorel – GDXinput'.

- This excel sheet has different tabs, where each contains a data input parameter.
- Through an MS Excel AddIn 'Ea Balmorel', developed by Ea Energy Analyses, the tabs can be converted to separate input *.gdx* files.

These *.gdx* files are included by the model in the Balmorel.gms code.



Why using the GDXinput file?

The using the GDXinput file ensures that the input data and the GAMS code are strictly separated, making it easier for the operator to use the model, without the need to know the GAMS language.

It gives the Balmorel user a structured tool with a good overview of all sets and parameters in the model. The GDXinput file has built in error-prevention when creating data files, so that obvious data inconsistencies will not occur.

The Balmorel toolbox for MS excel can be adapted and expanded with additional functionality later on.

First step: Install Balmorel add-in for MS Excel

Receive the folder called "EaBalmorel 32x64". Copy it somewhere on the machine. Run the set-up-exe file (follow instructions). Do not remove the other files!

This will install an Excel add-in called "Ea Balmorel", which will enable creating GDX input files with Excel. Open Excel and make sure the "Ea Balmorel" tab is visible on the top of the sheet.

The functionality within the add-in will only apply to sheets which contain a tab called "SET_LIST".

You are now ready to use the "Balmorel – GDXInput" file!

Types of model input to Balmorel

The GDXinput file recognizes the following 4 types of input files:

- **Scalars**: These are constants used in the model
- **One dimensional sets**: These are just lists of a certain category (e.g. countries in the model: CCC and regions in the model RRR)
- **More dimensional sets**: These are links between several one-dimensional sets.
  (e.g. which regions are in which countries CCCRRR)
- **Parameters:** These contain values for certain elements of one or more dimensions sets
  (e.g. demand per region DE(RRR) or investment costs for connected regions XINVCOST(RRR,RRR).

Different tabs in the Balmorel - GDXInput

The GDXinput file uses different tab with 5 kind of functionality:

- **SCALARS:** This is a single tab containing all scalars in the model
- **SET_LIST:** This is a single tab containing all one-dimensional sets in the model
- **Set tabs:** Several tabs, each containing one single more-dimensional set (e.g. CCCRRR)
- **Parameter tabs:** Several tabs, each containing one single parameter (e.g. DE)
- **Background tabs:** Normal tabs without special functionality which can be used for background calculations.

In the GDXinput file, colours are used to differentiate tabs. The Scalar tab is purple, the SET_LIST and set tabs are red, the parameter tabs have a colour depending on the parameter type, background tabs do not have any colour.

One dimensional sets

YYY	SSS	TTT	T	CCCRRRAAA	CCC	RRR	AAA	GGG	G
			TTT		CCCRRRAAA	CCCRRRAAA	CCCRRRAAA		GGG
1995	S01	T001	T001	Country1	Country1	Prettyregion	Prettyarea	Coal_Technology	Coal_Technology
1996	S02	T002	T002	Country2	Country2	Uglyregion	Uglyarea	Wind_technology	Wind_technology
1997	S03	T003	T003	Country3	Country3	Greenregions	Greenareas	NG_technology	NG_technology
1998	S04	T004	T004	Prettyregion		Coalregion	Coalarea	Solar_Technology	Solar_Technology
1999	S05	T005	T005	Uglyregion		Bigregion	Bigarea	Hydro_Technology	Hydro_Technology
2000	S06	T006	T006	Greenregions		Smallregion	Smallarea	Electricity_Storage	Electricity_Storage
2001	S07	T007		Coalregion		Emptyregion	Emptyarea	More_Wind	More_Wind
2002	S08	T008		Bigregion			Windarea1	More_Solar	More_Solar
2003	S09	T009		Smallregion			Windarea2	CCGT_Tech	CCGT_Tech
2004	S10	T010		Emptyregion			Hydroarea1	More_Hydro	More_Hydro
2005	S11	T011		Prettyarea			Hydroarea2	Run-of-River	Run-of-River

SET_LIST

In the SET_LIST tab, all the one dimensional sets are located. These can be used as indices for more dimensional sets and parameters.

The tab has a specific set-up:

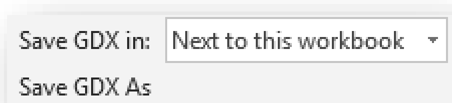
- Row 1: In the first row, the name of the one-dimensional sets is given
- Row 2: In the second row, if it exists, the name of the parent set (set of which the current set is a subset) is written (e.g. CCCRRRAAA is the parent set of CCC and CCC is a subset of CCCRRRAAA).
- Row 3 and downwards: From the third row down, the set elements are listed.

To create a new set, simply add more column to the right of the sheet, keeping the existing structure.

Creating .gdx files for one dimensional sets

When the sets that are listed in the SET_LIST tab are ready, they can be converted to .gdx input files.

Depending on where you want to save the set, in the 'Ea Balmorel' tab, select the location from the dropdown menu (includes all locations in current folder and 2 folders up that contain a balopt.opt file) or "Next to this workbook", which is recommended. And click "Save GDX in": If another location should be selected, choose "Save GDX as". A .gdx file of the set of the active cell will be created in the chosen location. Remember to locate the input files in the right folder, keeping in mind the folder hierarchy!



More dimensional sets

More dimensional sets are used to connect one-dimensional sets.

For example, all the regions which are within one country would be linked in the more dimensional set CCCRRR.

In the tab for more dimensional sets the following fields are relevant:

- Field B1: Name of the set
- Fields B2, C2, (D2, E2, …): Indices of the more dimensional set, these are the names of the one-dimensional sets which should be linked)
- Fields B3, C3, (D3, E3, …): Indicate for the indices above how they should be ordered in the tab.
- Fields J11 and downwards: Name of indices which are "Row"
- Fields K10 and right: Name of the indices which are "Column"
- Fields K11 and right and downwards: Names of indices which are "List"

To create a new more dimensional set tab, click the "Insert set" icon in the "Ea Balmorel" Add-in, enter the name of the set and the name of the tab it should have in Excel (recommended same names)

To save, press "Save GDX in" or "Save GDX as" when the tab is active.

More dimensional set as rows

	A	B	C
1	SET NAME	CCCRRR	
2	INDICIES	CCC	RRR
3	TYPE	ROW	LIST

Country1	Prettyregi	Greenregi	Bigregion
Country2	Coalregioı	Uglyregioı	Smallregion
Country3	Greenregions		

More dimensional set as columns

	A	B	C
1	SET NAME	CCCRRR	
2	INDICIES	CCC	RRR
3	TYPE	COLUMN	LIST

	Country1	Country2	Country3
	Prettyregi	Coalregioı	Greenregions
	Greenregi	Uglyregion	
	Bigregion		

Most important sets

Set name	Description
One dimensional sets	
CCCRRRAAA	All countries, regions and areas (gross list of all geography input)
CCC	All countries. Parent set CCCRRRAAA
C	Simulated countries. Parent set CCC
RRR	All regions. Parent set CCCRRRAAA
IR	Simulated regions Parent set RRR
AAA	All areas. Parent set CCCRRRAAA
IA	Simulated areas. Parent set AAA
YYY	All years
Y	Simulated years. Parent set YYY
SSS	All seasons in a year (S01 to S52).
S	Simulated seasons. Parent set SSS
TTT	All time-steps per season (T001 to T168)
T	Simulated timesteps. Parent set TTT
GGG	All generation technologies
G	Simulated generation technologies. Parent set GGG
FFF	All fuels
More dimensional sets	
CCCRRR	Regions belonging to countries (CCC,RRR)
RRRAAA	Areas belonging to regions (RRR,AAA)
ALLOWEDINV_STAND	Types of investment options (INVTYPE,GGG)
ALLOWEDINV	Specific investment options for an area (AAA,GGG)

Parameters

Parameters are used to assign values to (a combination of) one dimensional sets.

For example, the demand in year X and region Y can be set in the parameters DE(YYY,RRR).

In the tab for parameters the following fields are relevant:

- Field B1: Name of the parameter
- Fields B2, C2, (D2, E2, …): Indices of the parameter, these are the names of the one-dimensional sets which should be linked)
- Fields B3, C3, (D3, E3, …): Indicate for the indices above how they should be ordered in the tab.
- Fields J11 and downwards: Name of indices which are “Row” (columns left above may also be used in case there are more “Row” indices).
- Fields K10 and right: Name of the indices which are “Column” (rows above may also be used in case there are more “Column” indices).
- Fields K11 and right and downwards: Values of the parameter

To create a new parameter tab, click the “Insert parameter” icon in the “Ea Balmorel” Add-in, enter the name of the parameter and the name of the tab it should have in Excel (recommended same names, with different suffix if useful)

To save, press “Save GDX in” or “Save GDX as” when the tab is active.

Example

	A	B	C
1	PARAMET	DE	
2	INDICIES	YYY	RRR
3	TYPE	ROW	COLUMN

	Prettyregion	Greenregions	Coalregion	Smallregic	Bigregion	Emptyregic	Uglyregion
2018	48.191.667	11.125.000	58.850.000	1.682	40.159.722	9.270.833	49.041.667
2019	54.423.667	12.605.000	66.430.833	1.683	45.353.056	10.504.167	55.359.028
2020	60.655.667	14.085.000	74.011.667	1.683	50.546.389	11.737.500	61.676.389
2021	66.887.667	15.565.000	81.592.500	1.684	55.739.722	12.970.833	67.993.750
2022	73.119.667	17.045.000	89.173.333	1.685	60.933.056	14.204.167	74.311.111
2023	79.351.667	18.525.000	96.754.167	1.686	66.126.389	15.437.500	80.628.472
2024	87.786.833	20.662.667	105.969.667	1.687	73.155.694	17.218.889	88.308.056
2025	96.222.000	22.800.333	115.185.167	1.688	80.185.000	19.000.278	95.987.639
2026	104.657.167	24.938.000	124.400.667	1.688	87.214.306	20.781.667	103.667.222
2027	113.092.333	27.075.667	133.616.167	1.689	94.243.611	22.563.056	111.346.806
2028	121.527.500	29.213.333	142.831.667	1.690	101.272.917	24.344.444	119.026.389
2029	132.249.167	31.471.167	155.471.167	1.691	110.207.639	26.225.972	129.559.306
2030	142.970.833	33.729.000	168.110.667	1.692	119.142.361	28.107.500	140.092.222

Most important parameters

Below, the most important parameters are listed with a description. More parameters will be used in add-ons (e.g. policies)

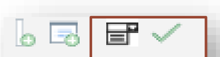
Parameter	***Indices***	**Description**
GKFX	*YYY,AAA,GGG*	**G**eneration capacity(**k**) **fix**ed. Yearly capacities of generation technology in each area (MW).
GDATA	*GGG,GDATASET*	**G**eneration **data**.
INVESTMENTS	*AAA*	Assign investment category to areas (# of type)
FDATA	*FFF,FDATASET*	**F**uel **data**. Containing emission and RE share.
FUELPRICE	*YYY,AAA,FFF*	**Fuel price** per year and area (money/GJ).
DE	*YYY,RRR*	**D**emand **e**lectricity per year and region (MWh).
DE_VAR_T	*RRR,SSS,TTT*	**D**emand **e**lectricy **var**iation (normalized)
DISLOSS_E	*RRR*	**Dis**tribution **loss** of **e**lectricity (%).
XKINI	*YYY,RRR,RRR*	Transmission capacity between regions (MW)
XINVCOST	*RRR,RRR*	Transmission investment costs for new lines (money/MW)
XMAXINV	*YYY,RRR,RRR*	Maximum transmission investment in each year (MW)
TAX_GE	*YYY,AAA,GGG*	**Tax** on **g**eneration of **e**lectricity (money/MWh)
TAX_GF	*YYY,AAA,GGG*	**Tax** on input **f**uel for **g**eneration (money/GJ)
FKPOT	*CCCRRRAAA,FFF*	Maximum technical **pot**ential per fuel (MW)
GEQF	*YYY,CCCRRRAAA,FFF*	Exact annual fuel use per **f**uel (GJ)
GMAXF	*YYY,CCCRRRAAA,FFF*	**Max**imum annual **f**uel use per fuel (GJ)
GMINF	*YYY,CCCRRRAAA,FFF*	**Min**imum annual **f**uel use per fuel (GJ)
M_POL	*YYY,MPOLSET,CCC*	Limit or tax emissions per country
NOINVF	*YYY,CCCRRRAAA,FFF*	If value is 1, from that year on, no **inv**estments in certain **f**uel. If value is 2, **inv**estments allowed again

More important parameters

Parameter	*Indices*	Description
WTRRSFLH	*AAA*	Hydro with **res**ervoir **F**ull **l**oad **h**ours (hours)
WTRRSVAR_T	*AAA,SSS,*	Hydro with **res**ervoir inflow **var**iation profile (normalized)
HYRSDS	*AAA, HYRSDSDATA, SSS*	Hydro reservoir data
WTRRRFLH	*AAA*	Hydro **r**un-of-**r**iver **F**ull **l**oad **h**ours (hours)
WTRRRVAR_T	*AAA,SSS,TTT*	Hydro **r**un-of-**r**iver inflow **var**iation profile (normalized)
WND_SPEED_T	*AAA,SSS,TTT*	**Wind speeds** (m/s)
WNDDATA	*AAA,WNDDATASET*	Information about **wind** speeds
GWNDDATA	*GGG,WNDDATASET*	Information about **wind** technologies
WNDFLH	*AAA*	**Wind FLHs** (hours)
WND_VAR_T	*AAA,SSS,TTT*	**Wind** production **var**iation profile (normalized)
SOLEFLH	*AAA*	**Solar FLHs** (hours)
SOLE_VAR_T	*AAA,SSS,TTT*	**Solar** production **var**iation profile (normalized)
SOLEFLHDEVELOP	*YYY,RRR*	**Develop**ment of **solar FLH** of technologies (ratio)

More options for Balmorel GDXinput file

In order to validate the data in the spreadsheet, the two last buttons can be used to either validate the indices or validate the value in the active sheet.



The sheet has error prevention built-in so that faulty combinations or wrong index names are not allowed

When setting up a whole new model, it can be useful to press "Save all" to output all scalars, sets and parameters.

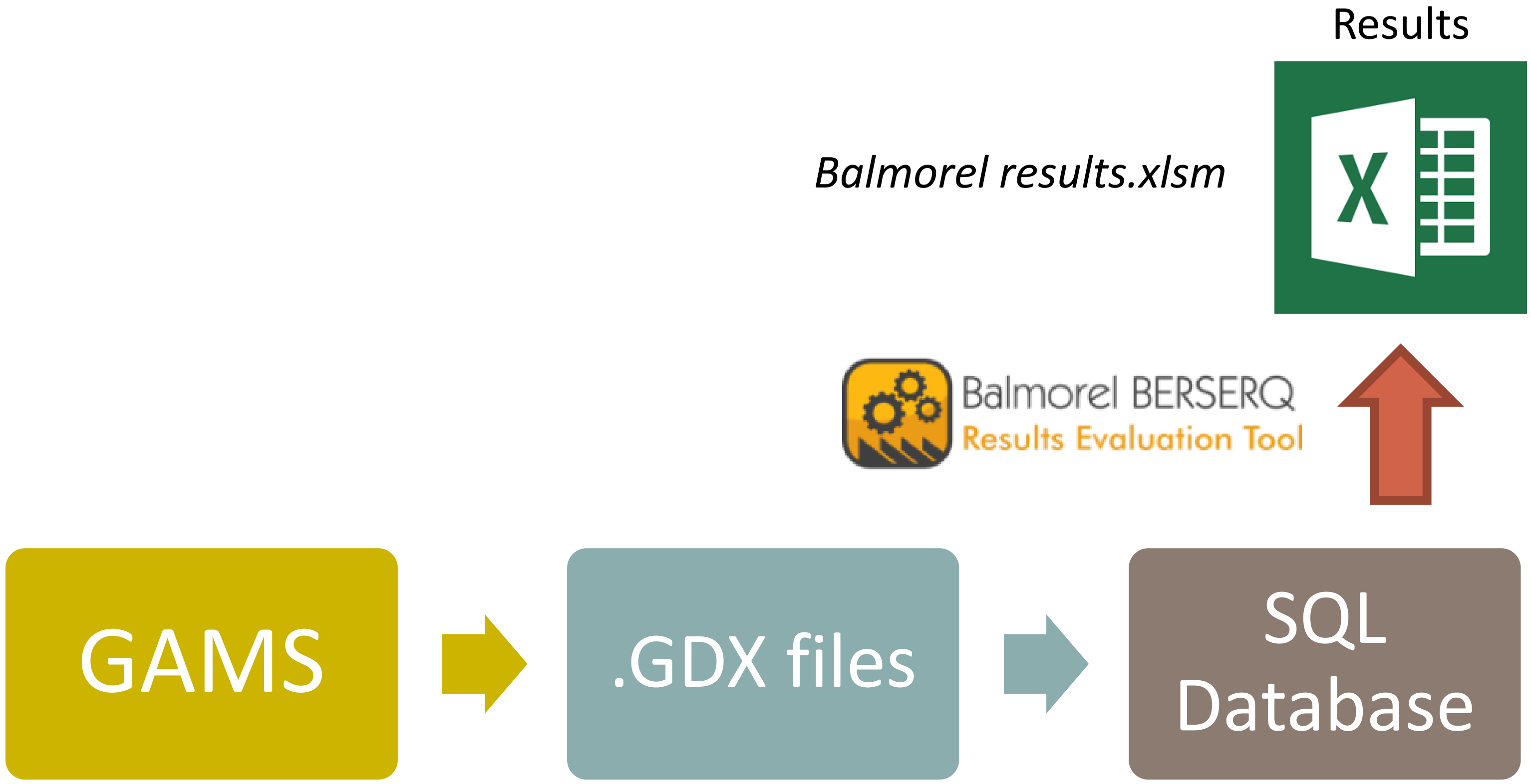
OUTPUT AND RESULT HANDLING

Showing different Balmorel results in a convenient way

Output of Balmorel

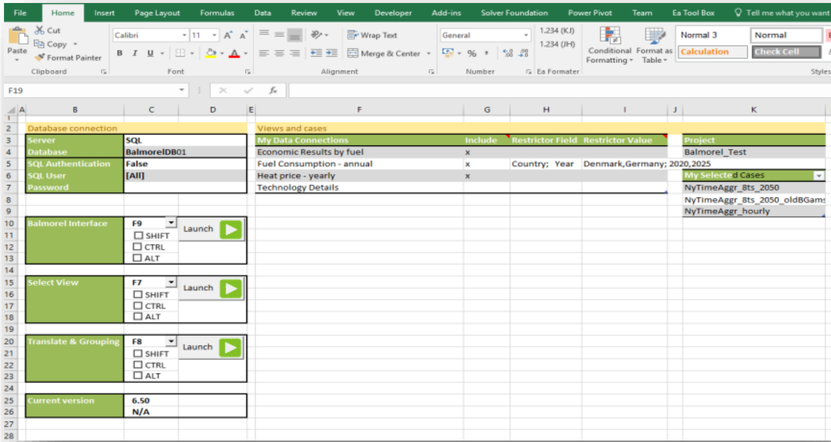
GAMS creates *.gdx* files as result output, which are then transferred to an SQL Database.

- The database is developed to create specific views such as Power generation per timestep, Economy results by area, technology and fuel, Electricity prices per region, Invested generation capacity per area, and much more.
- A MS Excel sheet named 'Balmorel Results' is developed for loading and analyzing these result views from the database.



BERSERQ tool in detail

BERSERQ interface



BERSERQ interface functions

The BERSERQ interface is an interface developed by Ea Energy analyses, used to view, illustrate and analyze Balmorel results in excel with the help of pivot tables. The main functionality is seen in the "Administration" tab. Important functions are:

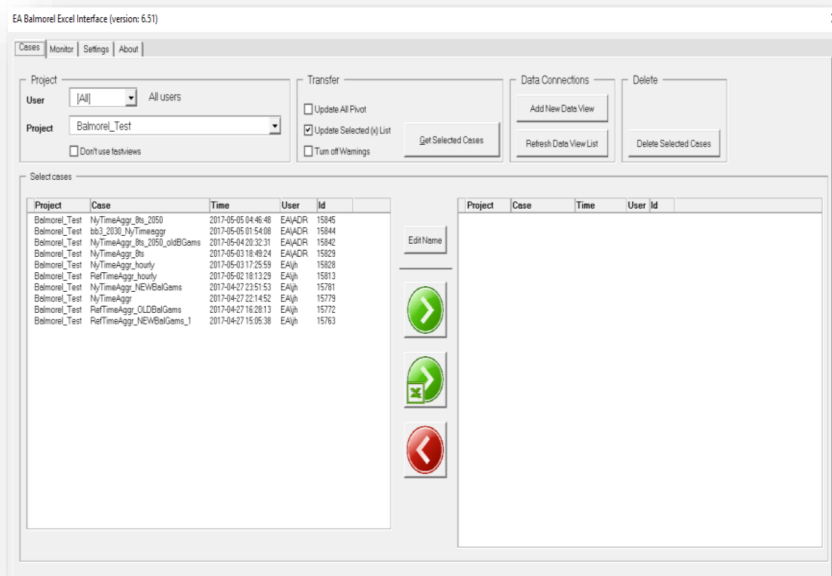
- *Balmorel interface*: where it is possible to load all the scenarios needed for the analysis.
- *Views selection*: select only the views needed for the analysis.
- *Translate and Grouping*: *Grouping* allows to group more features under the same **Fuel Type, Technology, Country and Case Name**. *Translating* gives the possibility to translate Balmorel names to more efficient ones.

How to load a Case

With BERSERQ it is possible to load one or more scenarios.

- They can be loaded from the *Balmorel interface* function.
- After pressing *Launch* (or using the shortcut selected) the screen shown in the right figure appears.
- Select the *User* who made the run and the relevant *Project.*
- The scenarios are then listed and can be chosen by selecting them and pressing the first green arrow. To select the scenarios that are already in the spreadsheet, select the second green arrow. When you made a mistake select the scenario in the right-hand list and press the red arrow.
- When all the cases needed are on the right side (blank in the figure), load them to MS Excel by pressing *Get Selected Cases.* they Decide which pivot tables to automatically update: All, Selected ones (see view filtering) , or none (leave all boxes unckecked).
- It is possible to filter the loaded cases from the pivot table *My Selected Cases* shown in the figure above (*BERSERQ interface*).

Loading a Case interface

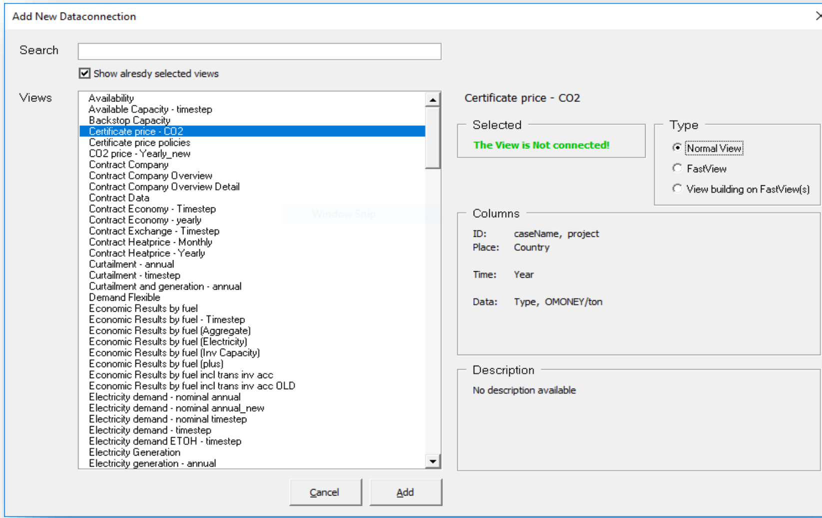


Views selection

In order to keep the MS Excel sheet light, BERSERQ allows to select only the views needed for the analysis.

- They can be loaded from the *Select View* function.
- You can search for view in the Search bar
- After pressing *Launch* (or using the shortcut selected) the screen shown in the right figure appears.
- After selecting a view, on the right side it is possible to see different characteristics of it.
  - *Selected:* it shows if the view is already connected or not.
  - *Type:* it shows if it is a normal or fast view.
  - *Columns:* It tells the info about the features contain in the view.
  - *Description:* it gives a brief description of the selected view.
- From here, the views desired for the analysis can be chose by selecting them and pressing the *Add* button.

BERSERQ interface functions



Views filtering

It is possible to filter the views which are automatically updated when loading cases in the "My data connections" table shown in the right figure. Here, one can also restrict the data in each view

- The list of views that will be updated when using the "Update selected (X) list" on loading cases, can be chosen by placing an "X" in the *Include* column.
- Restriction fields can be chosen. In the *Restrictor Field* column, the user can write the name of the fields which needs to be restricted. (Seperated with "; ")
- Finally, the values to which the restriction fields should be restricted are written in the *Restictor Value* column in order to load only those for that views. Different values for one Restrictor field should be separate by "," (no spaces), to switch between restrictor fields, use ";".

BERSERQ interface functions

Views and cases

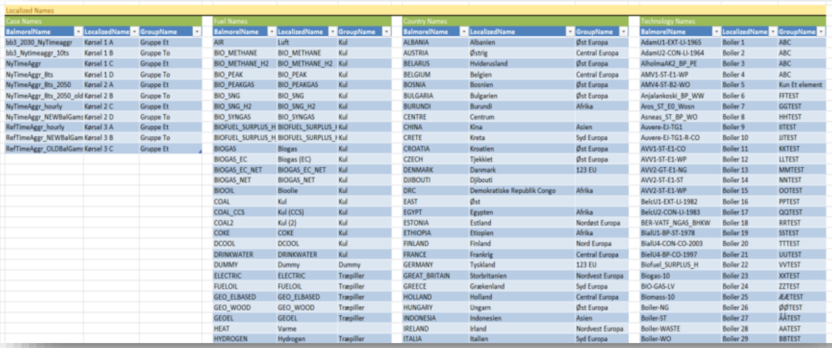
My Data Connections	Include	Restrictor Field	Restrictor Value
Economic Results by fuel	x		
Fuel Consumption - annual	x	Country; Year	Denmark,Germany; 2020,2025
Heat price - yearly	x		
Technology Details			

Project
Balmorel_Test

My Selected Cases
NyTimeAggr_8ts_2050
NyTimeAggr_8ts_2050_oldBGam
NyTimeAggr_hourly

The BERSERQ interface tables above show the loaded cases and views.
In this example, writing "Country; Year" in the Restrictor Field column and "Denmark,Germany; 2020,2025" in the Restrictor Value column will make sure that only data for Denmark and Germany in 2020 and 2025 is loaded when updating the Fuel Consumption pivot table.

Translate and Grouping tables

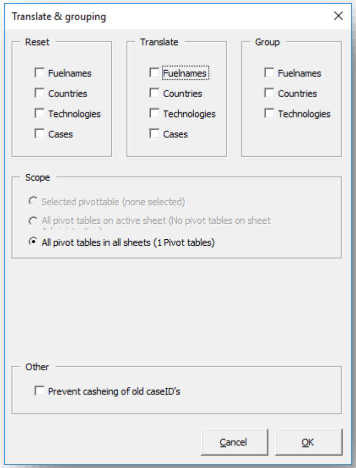


The names of groups (*GroupName* column) and translations (*LocalizedName* column) can be modified manually by directly changing them in the tables shown on the figure above, which are part of the BERSERQ interface.

Translate and Grouping

By pressing the *Launch* button (or using the shortcut selected) the window on the right figure appears.

- Here, the user can choose which translations and groups to apply on the pivot tables with results.
- In the *Reset* part, one can undo previous Translation/Grouping
- To use Translation/Grouping for just one pivot table or several pivot tables in one tab, Select the tab/table and use the shortcut key.



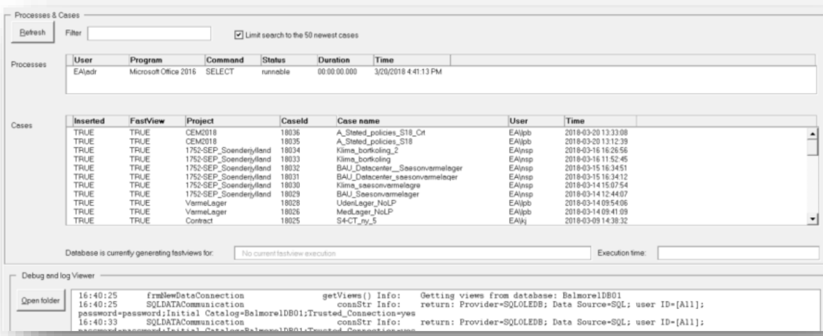
Monitoring of database work

The window on the right figure can be seen by pressing *Monitor* on the top left corner of the *Loading a case interface*.

- The first column (*Inserted)* indicates whether the data was sent correctly to the Database (if TRUE)
- The second column (*FastView)* shows if, in the database, the fast views have been created successfully (if TRUE).

When TRUE means completion, while FALSE means that the process is ongoing or not started. When a very long time passes for a case to be transferred to the database/created as fast view contact the person in charge of the database.

Monitoring interface



Ready to start the analysis

After launching the data, it is possible to select only the parameters required for the actual analysis.

- Pivot tables with all the features imported are automatically created.
- From these tables it is possible to filter the data by Fuel, Technology, Country, Case Name, Year..
- Pivot tables with all the cases and data selected are ready to be used for the analysis.

Balmorel output files

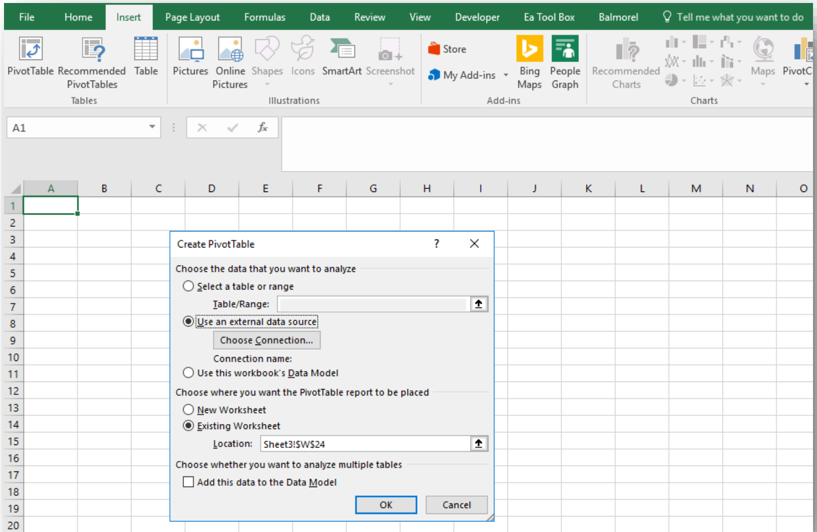
Results visualization

caseName	1_Main_new
Fuel	(Multiple Items)
Capacity Type	(Multiple Items)
Row Labels	**Sum of Power cap (MW)**
2015	64,051
2020	108,340
2025	118,730
2030	113,764
2035	136,844
2040	166,211
2045	195,848
2050	228,323
Grand Total	**1,132,109**

After loading the correct data needed for the analysis, relevant pivot tables can be generated to visualize of the results.

Pivot tables are in-built MS Excel objects. They are dynamic tables ideal for structuring and filtering a large amount of data.

How to create a pivot table



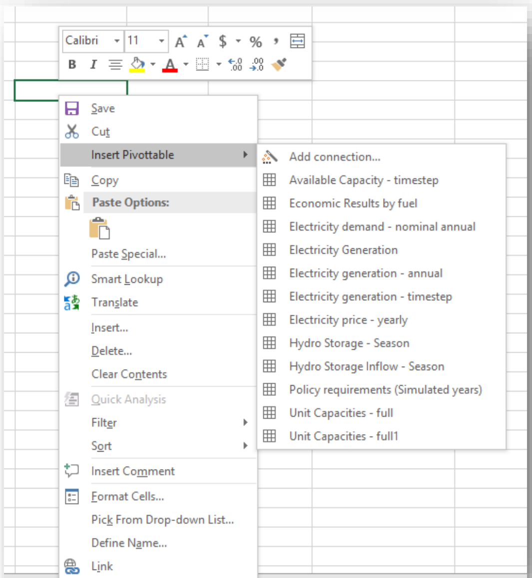
How to create a pivot table

The process to generate a pivot table is easy and straight forward.

- Go to the *Insert* section of the menu-bar in MS Excel.
- Select the cell where you want the table and press the *Pivot Table* icon (first on the left).
- Select "*Use an external data source*" and then press "*Choose connection*". Here you will find a list with all Views loaded in the BESERQ tool. (See Views selection section earlier). Select the view you want and press OK.
- Now the pivot table is created and the *Field list* is automatically opened, from which you can build the pivot table.

Shortcut to generate a pivot table

- Open the tab where you want to generate the pivot table.
- Right click and the window in the figure will appear.
- Choose the view you need for the pivot table.



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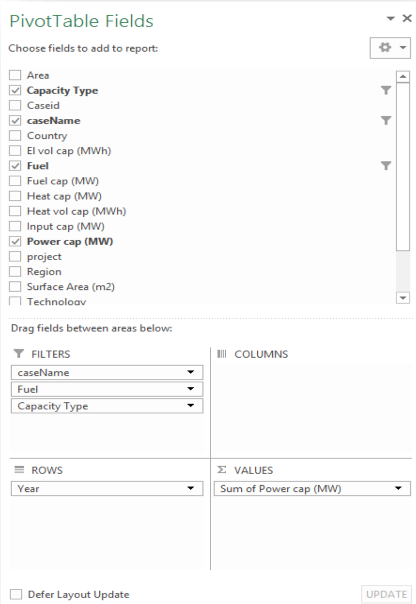
Field list

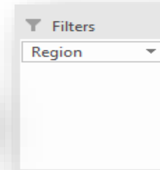


In the Field list window, the user can select and drag fields to 4 quadrants where they will have different functions:

- *Filters:* allows the user to select only some of the values in the field.
- *Rows/Columns:* allows the used to structure the table by deciding on the headers of the rows and columns.
- *Values:* fields in this quadrants will be the values in the table, structured by the row and column headers.

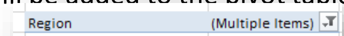
Filtering data

Not all data in a pivot table will always be useful for the analysis. There are two ways to filter the data to only the relevant information.



As a filter:

- Place the field in the *Filter* quadrant
- A filter field will be added to the pivot table at the top

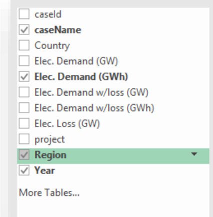


- Select the useful data items in the pivot table.

When used as row or column header:

- Place the field in row/column section
- Select items in the field list clicking the arrow down to the right.

When a field is has filtered values, a small funnel will appear next to it in the Field list.



Structuring data

To structure the pivot table and to decide on the structure the user can drag fields into the *Rows* or *Columns* quadrants. The values of the fields placed in the *Row/Column* quadrant will be used as headers for the rows/columns of the table.

The order in which the fields are placed changes the structure of the table. In the example below, fields “Country” and “Year” are placed in the *Row* quadrant. Left; First “Year” then “Country”, right vice versa.

Year	Country	Electricity Generation (GWh)
⊟2020	Country1	327.770
	Country2	308.997
	Country3	136.895
⊟2030	Country1	414.747
	Country2	333.742
	Country3	150.149
⊟2050	Country1	450.260
	Country2	299.976
	Country3	139.090
Grand Total		2.561.627

Country	Year	Electricity Generation (GWh)
⊟Country1	2020	327.770
	2030	414.747
	2050	450.260
⊟Country2	2020	308.997
	2030	333.742
	2050	299.976
⊟Country3	2020	136.895
	2030	150.149
	2050	139.090
Grand Total		2.561.627

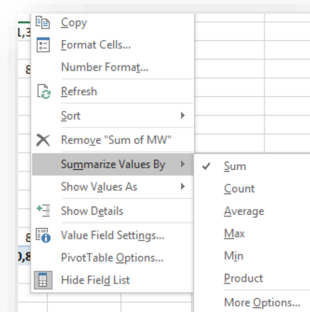
Data values

The values will be shown in the table should be placed in the *Value* quadrant. The fields in this section should always be numbers. In the Balmorel pivot tables they are often given a name containing the unit of the numbers (e.g. GWh or Money/MWh).

The values in the table will be aggregated if the pivot table needs to represent more than one value.

- Sum (e.g. sum of all generation in several regions)
- Count (shows the amount of aggregated values)
- Average (e.g. average of electricity price for all hours of the year)
- Max/Min.

Chose the preferred aggregation by right-clicking in the table and selecting *“Summarize Values By”*

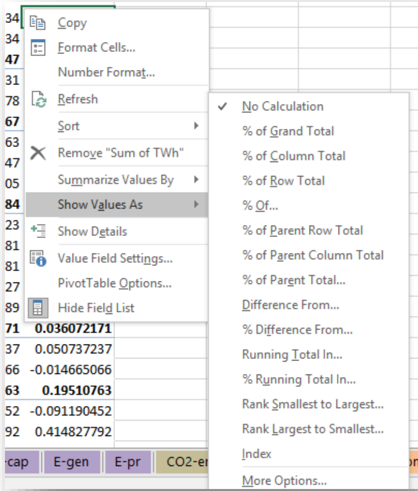


Show data as

It is possible to show the output values in different ways by right-clicking in the table and selecting *Show values as.*

It is for example possible to view the values in the table as a % of the row or column total, of the grand total.

It is also possible to see them as the difference between other data (e.g. the difference in value between two years or two scenarios)

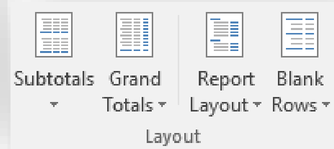


Design of the table

When the pivot table is selected, in the Pivot table tools – Design tab of MS Excel, some options are available to decide the design of the pivot table.

It is possible to turn the Subtotals or the Grand totals on or off for rows, columns or both.

In the Report layout button, you can decide between three layout-formats for the tables: compact form, outline form and tabular form. You can also select whether or not to repeat headings.



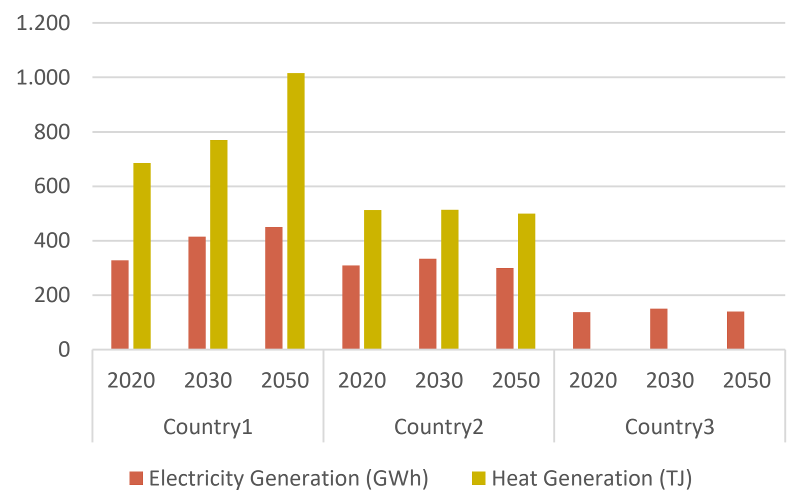
Pivot plot

After the pivot table is set-up as desired, it is possible to visualize the results by making a pivot plot.

When the pivot table is selected, Go to the "Insert" tab and chose the preferred plot type. The graph that will be created will automatically be a pivot plot and will stay linked to the pivot table just created.

When changing around in the pivot table, the pivot plot will update with every step.

Pivot plot



SVN - VERSION CONTROL

Keep an overview over GAMS code and input data

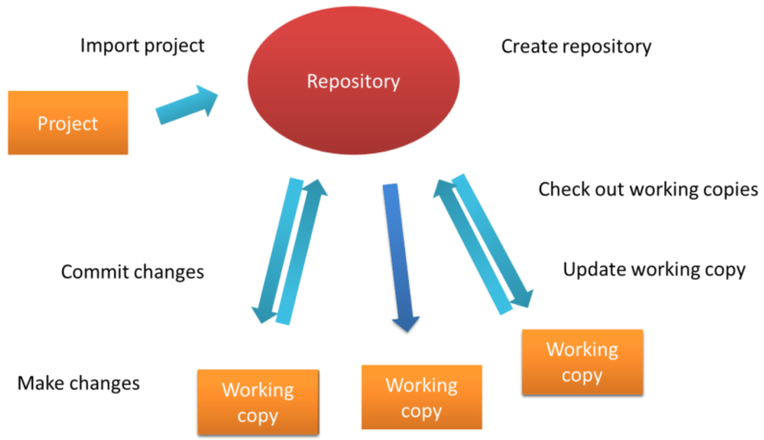
Version Control of Balmorel

What is Tortoise Version Control? Tortoise SVN is a subversion client which helps with management of changes to collections of information (e.g. documents, models, programs, websites, etc.)

Why is it useful?

- Many users work on the model at the same time and there is a need to keep track of all changes and subversions (history of changes)
- It is useful to always have an updated version which can easily be passed on to new users

SVN scheme



1. Install VPN

In the first step, download Tortoise SVN from the website https://tortoisesvn.net/downloads.html
Tortoise SVN is created under the GPL, general public license and is therefore free.
YouTube tutorial:
www.youtube.com/watch?v=zJdPFxBRIH8

2. Create a repository

After installation, it is necessary to create a repository, where all the tracking of changes will be kept. This should be a safe location where which all users can access, ideally a server.
To create a repository:

- -Create empty folder
- -Right click, Tortoise SVN, Create repository
- -Create folder structure

3. Add the Balmorel folder structure

As soon as the repository is set-up, choose the folders you want to version control (e.g. the Balmorel folder, containing the base folder and the project folders)

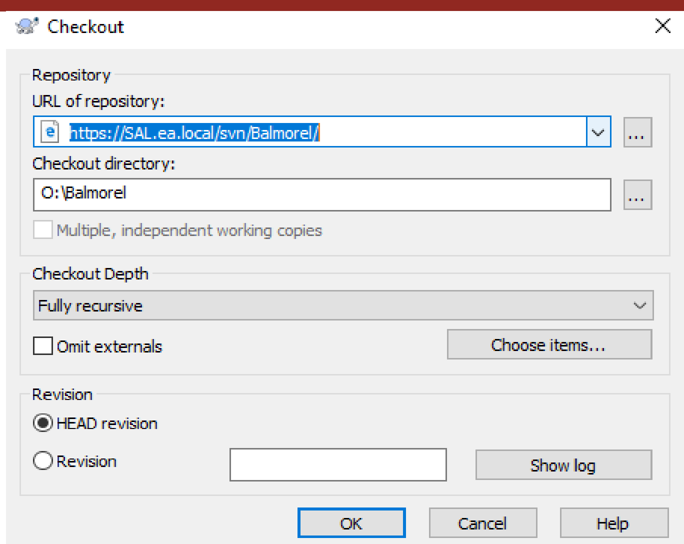
- Select the folder (Balmorel)
- Right click + Tortoise SVN + Import
- Make sure the correct repo-browser is used
- Add relevant a message

4. Checking out a new working copy

So far, only one version of the Balmorel files exist, the one that was imported to the repository in the previous step. The check-out an additional version (or working copy), for example for a second user do the following:

- Create an empty folder
- Right click and select “SVN checkout”
- Select the correct URL of the repository
- Choose fully recursive (to indicate that also subfolders should be checked-out)
- Keap HEAD revision selected

Checkout of working copy



5. Adding and committing files

When you are working on the working copy, small icons will indicate which files differ from the HEAD version (main version in the repository). When you are satisfied with the changes or additions, you can submit them to SVN HEAD version.

- To add new files: select the files and right click Tortoise SVN and then “Add”
- To commit files: Click on the folder you want to commit, right click and select “SVN commit”. You can see which file you are about to commit and select among them. It’s useful to add a description of you changes
- You can also double click the files you are about to commit to see the difference between the old and the new version. The same functionality for comparing files can be found in the executable TortoiseMerge.

6. Update working copy

When you are working on a working copy, the changes and additions other users commit to the HEAD version will not impact your working version. When you want to update your working version to the HEAD version you can:

- Check the log for updates (right click Tortoise SVN + show log).
- See if any of the updates are interesting/might mess up your runs
- Select the folder/files you want to update and right click + SVN update)

APPENDIX

The following is are list of some of the most important decision variables in Balmorel and a short description.

Variable	*..with indices*	Description
VOBJ	*VOBJ(AAA,G,S,T)*	**Obj**ective function (mill. USD16)
VGE_T	*VGE_T(AAA,G,S,T)*	**G**eneration of **e**lectricity for existing (exogenous) units (MW)
VGEN_T	*VGEN_T(AAA,G,S,T)*	**G**eneration of **e**lectricity for **n**ew (endogenous) units (MW)
VGH_T	*VGH_T(AAA,G,S,T)*	**G**eneration of **h**eat for existing (exogenous) units (MW)
VGHN_T	*VGHN_T(AAA,G,S,T)*	**G**eneration of **h**eat for **n**ew (endogenous) units (MW)
VGF_T	*VGF_T(AAA,G,S,T)*	**G**enerations **f**uel consumption rate for existing (exogenous) units (MW)
VGFN_T	*VGF_T(AAA,G,S,T)*	**G**enerations **f**uel consumption rate for **n**ew (endogenous) units (MW)
VX_T	*VX_T(IRRRE,IRRRI,S,T)*	E**x**port of electricity from region IRRRE to IRRRI (MW)
VXH_T	*VXH_T(IAAAE,IAAAI,S,T)*	E**x**port of **h**eat from area IAAAE to IAAAI (MW)
VGKN	*VGKN(AAA,G)*	**G**eneration capacity(**k**) **n**ew (endogenous) (MW)

Prepared by: Ea Energy Analyses, 2018