# 5.3 Energy Storage at utility scale as an enabler for $CO_2$ Mitigation

# Appendix C

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# Appendix C

## The energy systems model Balmorel-MX

This supplementary material presents a methodological and mathematical description of the energy systems model Balmorel [1, 2], with a focus on the version for Mexico, henceforth Balmorel-MX, used for this study. The model Balmorel might have other features, apart from the ones described here, which can be found in www.balmorel.com and in [3].

The objective of Balmorel is to maximize social welfare, which is equivalent to minimizing the total cost of the system, when assuming inelastic demands, and under the assumption of perfectly competitive markets. The model is written in the GAMS (General Algebraic Modeling System) language and the optimization problem is solved with cplex. In this study, Balmorel-MX, is run with simultaneous economic dispatch and optimization of investments in energy technologies for electricity and cogeneration, including power transmission capacities. The main characteristics of the model Balmorel-MX are summarized below:

- Balmorel is a bottom-up model, as it has a focus on supply technologies, including power transmission, and it is independent of market behavior. The model can be used in explorative scenarios, to analyze what would happen if… ?, and in normative scenarios, such as to assess what is the most cost-efficient way to achieve a desired greenhouse gas emission target [4].

- Balmorel is a partial equilibrium model, as it only optimizes power and cogeneration supply (as in Balmorel-MX), ceteris paribus to achieve the equilibrium. However, as already pointed out by Bohringer and Schmid [5], the impact of policy measures or uncertainties, such as changes in fuel prices or in learning curves, might not be restricted uniquely to the energy system, and it should be analyzed within a wider economic context if interrelations are important. The equation that represents the equilibrium between demand and supply of the single market considered, constitutes the market clearing price, taking as exogenous prices in other markets, the behavior of the agents, etc.

- The optimization is deterministic, and the parametric uncertainty of the scenarios is assessed through deferent local sensitivity analysis, varying one factor at a time, but without considering stochasticity as part of the optimization it-self. In addition, due to the fact that the full economy is not represented, as mentioned before, sensitivity analysis allows to consider the possible impacts of some parameters modelled as exogenous, which could get affected by the energy system.

- The equations of Balmorel-MX are linear, and it would be possible to run it as a mixed integer linear programming with discrete variables in order to represent economies of scale or the unit commitment problem. However, this has not been done during this study, due to the significant increase of computational time associated.

Balmorel-MX has three layers of spatial resolution: Country[1] 1, Regions that belong to a Country, and Areas that belong to a Region within a Country. Generation technologies are located in Areas, which represent individual geographical characteristics within a Region. The electricity demand is set at Region level and might be traded between Regions provided that there is a line for power transmission; however, electricity trade within a region is modelled as a copper plate without representing the power grid. Resource constraints and policies might be set at any geographical level desired: Country, Region and/or Area.

Balmorel-MX has three hierarchical levels of temporal dimensions. Investments and climate targets are set at a Yearly level. The Year is further divided into Seasons, that represent seasonal variations of resources, such as hydropower reservoir levels or biomass availability after harvesting. Each Season contains an equal number of Terms, which represent short-term dynamics of the system. In this study each year has been run with 12 Seasons and 168 Terms, which are equivalent to 12 full weeks (one representative week for each month) with an hourly resolution. Seasons and Terms are defined chronologically in Balmorel-MX within a Year to represent the behavior of hydro reservoir levels.

Balmorel might be run with different degrees of foresight between years (How much can be known or anticipated about the future?) and within the year of optimization, e.g. considering the water value of hydro reservoirs. In this study, Balmorel-MX is run:

- Myopic approach between years, every year is optimized without any knowledge about how the future might evolve. This method was chosen, as previous analysis shown that investments using a perfect foresight approach until 2050 (the latest year of this study), and a myopic approach, were similar; and considering the fact that solving the problem with perfect foresight increases considerably the computational time .

- Perfect foresight within the year of optimization. Hydropower reservoirs have the ability to foresee how the generation and demand of electricity is going to evolve over the year, in order to maximize the value of the water they store. Similarly, as the consumption of fossil fuels might be constraint by climate targets, its use is optimized during the year.

- No endogenous decommissioning of plants has been assumed, due to the absence of foresight between years of optimization that could led to sub-optimal decisions in the long-term for actions taken in the short-term. Mothballing of plants could have been considered, given the myopic approach of the exercise, but it was leave out of

[1] Country, Region, Area, Year, Season and Term are capitalized to denote specific Balmorel-MX notation

the scope of the present analysis, as some of these plants could be useful to provide ancillary services, which are not modelled.

- Barrier algorithm (also known as interior point method) was the fastest solving the problem with a less detailed temporal resolution; thus, it was chosen to conduct the full analysis.

A simplified mathematical formulation of the model Balmorel-MX is described below. The nomenclature of the sets, parameters and variables of the different equations can be found at the end of the document.

The objective function of Balmorel-MX, Equation 1, minimizes the cost of satisfying the electricity demand and process heat demand that could potentially be covered by cogeneration, at each Year ***y***, represented as ***Zy***, which includes the costs of providing electricity and process heat, including generation and transmission investments. A simplified mathematical representation of the objective function is as follows:

Minimize:

$$Z_y = + \sum_{a\in\mathcal{A}} \sum_{g\in\mathcal{G}} \sum_{s\in\mathcal{S}} \sum_{t\in\mathcal{T}} c^{vOP}_{y,a,g} \cdot p_{y,a,g,s,t} + \sum_{a\in\mathcal{A}} \sum_{g\in\mathcal{G}} c^{CAP}_{y,g} \cdot p^{new}_{y,a,g} + \\ + \sum_{a\in\mathcal{A}} \sum_{g\in\mathcal{G}} c^{fxOP}_{g} \cdot (p^{exist}_{y,a,g} + p^{new}_{y,a,g}) + \sum_{r,r'\in\mathcal{R}^{ex}(r)} c^{CAP}_{r,r'} \cdot p^{tr-new}_{y,r,r'} \quad (1.)$$

The variable costs of operation of the technology ***g***, $\boldsymbol{c^{v\,OP}_{y,a,g}}$, represent the variable operational and maintenance costs of the technology ***g***, plus the costs associated to fuel consumption and related environmental taxes (e.g. greenhouse gas emissions); thus, changing and evolving over the years ***y***, and being specific to each area ***a***. Total variable costs are a function of the endogenous variable for power and/or process heat generation from the technology ***g***, situated in the area ***a***, at the time ***y, s; t***.

The investment costs correspond to endogenous investments in new generating capacity, $\boldsymbol{p^{new}_{y,a,g}}$ at the beginning of the year ***y***, and the incurred capital costs, $\boldsymbol{c^{CAP}_{y,g}}$, which are a function of the year ***y***, as it considers exogenous learning curves. The latter are annualized using an annualization factor that is a function of the discount rate and the economic lifetime of the technology ***g***. Similarly, the investment costs for the endogenous expansion of power transmission lines between the regions ***r*** and ***r´***, $\boldsymbol{p^{tr-new}_{y,r,r'}}$, are calculated with an annualized value of the investment costs for that line, $\boldsymbol{c^{CAP}_{r,r'}}$.

The fix operational costs consider the exogenous, $\boldsymbol{p_{y,a,g}^{exist}}$, and endogenous $\boldsymbol{p_{y,a,g}^{new}}$, total installed capacity of the technology ***g*** in the area ***a*** at the beginning of the year ***y***, and the fix operational expenditures $\boldsymbol{c_g^{fx\,OP}}$ associated.

The optimization is subject to constraints, such as balancing of electricity supply and demand at each time period, technical constraints, resource availability constraints and regulatory constraints, among others [3]. Some of the constraints used in Balmorel-MX are illustrated below.

Equation 2 ensures that the electricity demand, $\boldsymbol{d_{y,r,s,t}^{el}}$, is met in all regions (geographical areas ***a*** are aggregated into transmission regions ***r***) and time periods. Electricity might be transmitted between regions, where the variable $\boldsymbol{p_{y,r,r',s,t}^{trans}}$ shows the amount of electricity exported from region ***r*** ∈ ***R*** to region ***r´*** ∈ $\boldsymbol{R^{exp}(r)}$, and the variable $\boldsymbol{p_{y,r,r',s,t}^{trans}}$ denotes the amount of electricity imported, including losses, from the region ***r´*** ∈ $\boldsymbol{R^{exp}(r)}$ towards ***r*** during the time period ***s, t***.

$$\sum_{a\in\mathcal{A}(r)}\sum_{g\in\mathcal{G}} p_{y,a,g,s,t}^{el} + \sum_{r'\in\mathcal{R}^{im}(r)} e_{r',r}\cdot p_{y,r',r,s,t}^{trans} - \sum_{r'\in\mathcal{R}^{ex}(r)} p_{y,r,r',s,t}^{trans} = d_{y,r,s,t}^{el}$$
$$\forall \quad y\in\mathcal{Y}, r\in\mathcal{R}, s\in\mathcal{S}, t\in\mathcal{T} \qquad (2)$$

Similarly, Equation 3 represents that all the process heat demand that could potentially be covered by either cogeneration or heat-only boilers, $\boldsymbol{d_{a,s,t}^{dh}}$, is satisfied in all areas and time periods.

$$\sum_{g\in\mathcal{G}} p_{y,a,g,s,t}^{ph} = d_{y,a,s,t}^{ph} \qquad \forall \quad y\in\mathcal{Y}, a\in\mathcal{A}, s\in\mathcal{S}, t\in\mathcal{T} \qquad (3)$$

Equation 4 represents the constraint of ow of a commodity, $\boldsymbol{p_{y,a,g,s,t}}$, at each time period ***y, s, t,*** given by the installed capacity of a dispatchable technology ***g*** in the area ***a***, which as aforementioned takes into account the exogenous and endogenous capacity, and the availability of the plant. This commodity is electricity supply for power plants and cogeneration technologies, and process heating for heat-only boilers.

$$p_{y,a,g,s,t} \le k_{y,a,g,s,t}^{D}\cdot(p_{y,a,g}^{exist} + p_{y,a,g}^{new}) \quad \forall \quad y\in\mathcal{Y}, a\in\mathcal{A}, g\in\mathcal{G}^D, s\in\mathcal{S}, t\in\mathcal{T} \qquad (4)$$

When the plant ***g*** is not dispatchable (wind, solar and hydro run-of-river), the generation is fixed at each specific time ***s; t*** and area ***a***, but it is possible to curtail its production, in case it is optimal for the system.

$$p_{y,a,g,s,t} + p^{curt}_{y,a,g,s,t} = k^{ND}_{y,a,g,s,t} \cdot (p^{exist}_{y,a,g} + p^{new}_{y,a,g}) \;\; \forall \quad y \in \mathcal{Y}, a \in \mathcal{A}, g \in \mathcal{G}^{ND}, s \in \mathcal{S}, t \in \mathcal{T} \tag{5}$$

Equation 6 describes the limits to power transmission between interconnected regions ***r; r´*** given by the exogenous, $\boldsymbol{p^{tr-exist}_{y,r,r'}}$, and endogenous, $\boldsymbol{p^{tr-new}_{y,r,r'}}$, capacity of the lines and their availability.

$$p^{trans}_{y,r,r',s,t} \leq k^{trans}_{y,r,r',s,t} \cdot (p^{tr-exist}_{y,r,r'} + p^{tr-new}_{y,r,r'}) \quad \forall \quad y \in \mathcal{Y}, r \in \mathcal{R}, r' \in \mathcal{R}^{ex}(r), s \in \mathcal{S}, t \in \mathcal{T} \tag{6}$$

Limitations to greenhouse gas emissions are calculated as a function of the fuel consumed in the country for a specific activity, and the global warming potential of that fuel. However, it should be noted that very often only selected time slices are run within a year; therefore, each time slice must be given a relative weight within the year in order to assess annual constraints.

$$GHG^{Cap}_{y} \geq \sum_{a \in \mathcal{A}} \sum_{f \in \mathcal{F}} GW_f \sum_{g \in \mathcal{G}(f)} p^{fuel}_{y,a,g,s,t} \quad \forall \quad y \in \mathcal{Y} \tag{7}$$

Availability of resources, water storage in hydro reservoirs, as well as operational restrictions, e.g. related to operation of combined heat and power plants, are not described in the equations above; however, they are all constraints of the optimization in Balmorel-MX, which can be consulted in the references provided.

# Nomenclature

| Sets | |
|---|---|
| $\mathcal{A}$ | Areas |
| $\mathcal{A}\ (r)$ | Subset of areas in region $r \in R$ |
| $\mathcal{F}$ | Fuel |
| $\mathcal{G}$ | Technologies |
| $\mathcal{G}^{D}$ | Subset of technologies that are dispatchable |
| $\mathcal{G}^{D\ N}$ | Subset of technologies that are non-dispatchable |
| $\mathcal{G}\ (f)$ | Subset of technologies that consume the fuel $f$ |
| $\mathcal{R}$ | Regions |
| $\mathcal{R}^{exp}\ (r)$ | Subset of regions that region $r \in R$ can export to |
| $\mathcal{R}^{imp}\ (r)$ | Subset of regions that region $r \in R$ can import from |
| $\mathcal{S}$ | Seasons |
| $\mathcal{T}$ | Time periods in a season |
| $\mathcal{Y}$ | Years |
| Variables | |
| $\boldsymbol{p_{y,a,g}^{new}}$ | Endogenous investments in technology $g$ in area $a$ at the year $y$ |
| $\boldsymbol{p_{y,r,r'}^{tr-new}}$ | Power Transmission investments between Region $r$ and $r'$ at the year $y$ |
| $\boldsymbol{p_{y,r,r',s,t}^{trans}}$ | Transmission of electricity between region $r$ and region $r'$ in the time period $s$, $t$ at the year y |
| $\boldsymbol{p_{y,a,g,s,t}}$ | Commodity level in area a of technology $g$ in the time period $s, t$ at the year $y$ |
| $\boldsymbol{p_{y,a,g,s,t}^{curt}}$ | Curtailment of technology $g$ in area $a$ in the time period $s, t$ at the year $y$ |
| $\boldsymbol{p_{y,a,g,s,t}^{fuel}}$ | Fuel consumed by technology g in area $a$ in the time period $s, t$ at the year $y$ |
| $\mathcal{Z}_{y}$ | Total cost of the system for satisfying the energy demands at year $y$ |
| Parameters | |
| $\boldsymbol{c_{y,g}^{CAP}}$ | Annualized investment cost of technology $g$ at the year $y$ |
| $\boldsymbol{c_{y}^{fx\ OP}}$ | Fix Operational cost of technology $g$ |
| $\boldsymbol{c_{y}^{v\ OP}}$ | Variable operational cost of technology $g$ at the year $y$ |
| $\boldsymbol{d_{y,g}^{ph}}$ | Demand of process heat that could be supplied by cogeneration in the area $a$ in the time period s; t at the year y |
| $\boldsymbol{d_{y,r,s,t}^{el}}$ | Demand of electricity in the region r in the time period s; t at the year $y$ |
| $\boldsymbol{e_{r',r}}$ | Efficiency of power transmission between the regions r´ and r |
| $GHG_{y}^{Cap}$ | Greenhouse gas emission limit at the year $y$ |
| $GW_{f}$ | Global Warming potential factor of the fuel $f$ |
| $\boldsymbol{k_{y,r,s,t}^{D}}$ | Availability of the dispatchable technology g located in the area a in the time period s, t at the year y |
| $\boldsymbol{k_{y,a,g,s,t}^{N\ D}}$ | Availability of the non-dispatchable technology g located in the area a in the time period s, t at the year y |
| $\boldsymbol{k_{y,r,r',s,t}^{trans}}$ | Availability of the transmission line between the regions r and r´ in the time period s, t at the year y |
| $\boldsymbol{p_{y,a,g}^{exist}}$ | Existing capacity of technology g in the area a at the year y |

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