Water-Energy Co-Optimization: Analysis in the Latin-American Interconnection Context

Camila Santibáñez[1,2], Rodrigo Palma-Behnke[1,2], Marcia Montedonico[2], Francisca Herrera-Neira[2], Bárbara Blanco-Contreras[1], Marcelo Olivares[2,3]
[1] Department of Electrical Engineering, University of Chile
[2] Energy Center, University of Chile, Chile
[2,3] Department of Civil Engineering, University of Chile

Abstract

Population spread, energy demand growth, and water consumption will impose new challenges and constraints to water resources. The impact of climate change will modify the current rainfall pattern in Latin America altering the availability of water resources, where near 70% of freshwater withdrawals are used for agriculture. A strong interdependence of energy and water is recognized but current tools for conducting an integrated analysis are not addressing the complexity of the problem. This paper is aimed at identifying the effects of high solar energy penetration in the context of Latin America interconnections under climate change scenarios. For this purpose, a novel co-optimization model of energy and water is proposed, considering water use for irrigation and climate change effects for the year 2040. The results show that planning a system based on solar energy will modify water and energy allocations. Several scenarios and sensitivities show the impact of considering climate change, water use, and specific social impacts. A realistic assessment on high solar energy penetration at regional level requires the simulation of short-term operating conditions in the planning exercises.

Keywords: Water-Energy nexus, co-optimization, irrigation agriculture, climate change

1. Introduction

1.1 Motivation

According to World Bank and International Energy Agency (IEA) projections, world population will grow by almost 20% in 2040 in relation to 2018, and primary energy demand will also increase by 43% compared to the current policies stage. By 2040, water consumption in the energy sector is expected to grow about 85% compared to 2014, even though the agriculture sector will continue being the main consumer. Additionally, this increase in energy demand may result in an increment of greenhouse gases (GHG) emission and a deterioration in water quality. The impact of climate change will completely modify the intensity, frequency, seasonality and rainfall amount in Latin America (LATAM), altering the current scenario, and consequently, the availability of water resources. Chile and Argentina will particularly be affected in their hydroelectric potential, not only in the rainfall profile, but also in the glacial retreat in the Andes.

Hydroelectricity had 56% of LATAM electricity generation during year 2015, and 71% of freshwater withdrawals were used for agricultural purposes. In addition, agriculture is a key economic activity in the region. It is a land intensive/water user and supports social welfare in many countries. The relevance of the Water-Energy nexus is widely recognized, however analysis framework and current models are not able to cover all these aspects (IEA 2016, Ferroukhi et al. (2015) and Flammini 2014).

The relevance to face this issue from a regional perspective responds to the possibility of introducing large-scale solar energy power, promoted by decarbonization incentives and a decrease in electricity costs related to solar solutions. Thus, a fast increase of its relevance in power generation mix is expected. Therefore, energy systems shall become more flexible due to the variability and uncertainty this kind of technology delivers, in order to guarantee energy security. As mentioned before, this trend will be affected by changes in water availability in LATAM.

Electric interconnection in LATAM is a possible techno-economical strategy to deal with these challenges. It has the capability to increase the strength of the system and receive benefits from the resources on a complementary basis. However, beyond the benefits detailed by the interconnections at regional level, this strategy brings substantial political challenges that entail several difficulties in its implementation.

In brief, the aim is to move towards an integrated management of Water-Energy resources, identifying and incorporating variables of water use for irrigation, but also considering the impact of a greater development of

doi:10.18086/swc.2019.19.11 Available at http://proceedings.ises.org

solar energy in the region and interconnections towards a clean and renewable power system.

1.2 Current status

In recent years different entities such as the International Energy Agency (IEA 2016) , the World Bank (Rodriguez et al. 2013), the International Renewable Energy Agency (Ferroukhi et al. (2015)) and the United Nations (Flammini 2014) have made emphasis on the growth of the world population projected by 2040, which will result in an increase of the demand for energy and water resources, coupled with a growth in the demand for food, as well as economic, industrial activity and technological development.

The concern is that the availability of fresh water will be affected by the increasing pollution and climate change effects, which will add pressure in the energy sector due to a high interconnection between water and energy (IEA 2016).

In this context, the joint management and planning of energy systems and water resources is proposed as the best option to manage the water-energy nexus in a future context. However, it is not a simple task given the current separation between the management and planning of each sector. So, it is important to analyze how decisions made in one sector would affect others, in order to support decision-making (Ferroukhi et al. (2015), Flammini 2014).

Additionally, an uncoupled approach has been proposed, by diversifying the energy matrix with sources that do not have an intensive use of water, such as wind and photovoltaic generators. Concurrently, the interconnection of the regional electrical systems has been proposed, given that climate change will affect water availability in several ways depending on the geographical location, and this interconnection shall allow a better use of resources (IEA 2016).

Although the option of interconnecting electrical systems is interesting, experience says that it is a political challenge, despite several studies ensuring the feasibility and benefits at technical and economic levels of a large-scale interconnection.

IRENA (Ferroukhi et al. (2015)) mentions that in order a nexus-based approach to be embraced by the managements of sectors, there is a wide range of quantitative and qualitative tools and methods for decision-making, depending on the purpose of the analysis and the access to data. Within the quantitative tools, IRENA defines two possible approaches: a fully integrated one, where all the linkages between water and energy are represented; and another that considers the link but with an entry point, i.e. the influence of one sector on the other. An example of the latter approach is the methodological proposal provided by the United Nations (Flammini 2014). Its entry point is food, and its influence is estimated in the energy and water sectors. On the other hand, the MARKAL/TIMES model uses energy (Loulou 2005) as its entry point.

On the other hand, (Khan et al. 2017, Shannak et al. 2018, Dai et al. 2018) review models and methodologies, proposed in the literature, for the integration of water and energy sectors. These models and methodologies have been carried out from a systemic perspective (i.e. without considering specific issues on processes and technologies), so that the main challenge of this integration will be to match the temporal (second, hours, days, months, years) and spatial scales (by basin, city, region or international) (Dai et al. 2018) of each sector. Another challenge highlighted in (Khan et al. 2017) for the integration of both sectors is the way in which multi-purpose reservoirs of the systems are managed.

A recurrent way to manage this nexus in the literature, is to modify energy models in order to integrate water systems. This integration can be through constraints or an addition to the objective function. Also, there are methodologies where single energy and water models are connected through explicit links in order to model linkages. Despite the advantage of having simulation models such as WEAP (water), LEAP (energy) and optimization models such as IWROM (water), MARKAL/TIMES (energy), interconnecting them have a high level of complexity regarding computing resources (Khan et al. 2017).

Among the oldest operating models mentioned, the hydrothermal coordination stands out, which is an energy model with water system constraints. In that model, the reservoirs operation is optimized through a multi-year and stochastic approach, for example with SDP and SDDP techniques. In the models proposed by (Pereira-Cardenal et al. 2016) and (Rojas 2018), a long-term hydrothermal coordination model is modified, including the benefit (or associated cost) related to irrigation supply (or unmet supply) in the objective function.

On the other hand, in (Bouckaert et al. 2014) and (Cohen et al. 2014) the TIMES and ReEDS, the energy optimization model is modified accordingly, in order to represent the demand for water in the cooling of thermal plants. In (Rodriguez et al. 2013) the TIMES model is also modified but without a representation of the physical water system. Whereas, the Stockholm Environment Institute (Welsch et al. 2014), integrates the WEAP water analysis module and the LEAP energy planning model, both simulation models, and includes the use of water in agriculture and human consumption.

Out of the reviewed models, there is no model that optimizes the operation and planning of the water-energy nexus including all the linkages identified. Some models consider transboundary systems, being the application in the watersheds of Spain (Pereira-Cardenal et al. 2016) the largest one territorially speaking.

Based on the literature reviewed, the types of modeling can be analyzed through seven dimensions:

- *Type of study:* Qualitative and/or quantitative approaches.
- *Model type:* If the type of study is quantitative, it can be developed through a simulation model or by an optimization model.
- *Type of integration of the nexus:* The literature shows that the nexus has been modeled through energy models that incorporate water constraints. Also, energy and water models linked to each other have been used. And finally, integrated models have been proposed through multi-objective functions.
- *Time scale:* One of the greatest challenges for modeling the nexus has been to make the time scales of both sectors match, so that this choice has a major importance on the modeling.
- *Spatial scale*: Most of the studies that consider, for example, irrigation of agriculture, have used a spatial scale at basin level. However, at the electrical level, the spatial scale is usually regional or even cross-border. Matching both is a challenge for modeling.
- *Aggregation level of reservoirs:* (Pereira-Cardenal et al. 2016) shows the differences when changing the aggregation level of reservoirs for hydroelectricity and irrigation. On the other hand, in studies of regional electrical integration such as the IDB (Paredes 2017), reservoirs and hydroelectric power plants are modeled in cascade.
- *Modeled links:* There are several links between the energy sector and water resources that can be studied. According to the literature review, the most common is the water consumption by energy processes, energy consumption by water processes and the modeling of multipurpose reservoirs.

This taxonomy in modeling will work as the basis for the co-optimization model proposed in this work.

1.3 Paper contribution and structure

This research develops a novel decision-making tool, based on the analysis in the context of regional energy integration, regarding the opportunities offered by the co-optimization of water resources and electrical power systems. Several scenarios and sensitivities show the impact of considering climate change and the use of water in agriculture.

Sections 2 and 3 present the proposed model and methodologies required in each of the stages. Then, Section 4 and 5 detail the implementation of the proposed model and its application in the case of the regional integration of LATAM, presenting the results and discussion. Section 6 presents the main conclusions of this research and future work.

2. Proposed Co-optimization Model

The proposed Water-Energy co-optimization model incorporates the economic value and constraints of water resources and their uses alternative, in an existing energy model based on hydrothermal coordination. For a better representation of the dynamics between both resources, a deterministic, perfect-foresight, linear and hourly centralized operation model is proposed. The time horizon used is one year.

The minimization is subject to reliability and security constraints, reservoir energy balances, demand side management constraints and generation limits for solar photovoltaic and wind plants, given by primary resource availability, introduced in a deterministic way.

Given the research scope, the aggregation level of power and irrigation systems shall be at country level. Although there is not stochastic treatment and therefore the operation decisions will have a degree of uncertainty, the time treatment would account for systemic effects, which is the main purpose of this research.

2.1 Objective function

The objective function minimizes the sum of the total operating costs associated to power generation units and unserved energy, and the total cost of unmet irrigation in system basins.

$$\min_{p,w} \sum_t \left[\sum_{j=1}^{N_{gen}} C_j\left(P_{j,n,t}\right) + \sum_n c^{LS} p_{t,n}{}^{unserved} + \sum_h CI^{unmet}\left(w_{t,h}\right)\right] \qquad \text{(eq. 1)}$$

2.2 Constraints

Power balance: In each node n of the system for all time period t, the total power generated plus discharge or charge energy from energy storage system, potential unserved and net injected power to the node, shall be equal to the real load. Transmission losses are not being considered.

$$\sum_j P_{j,t,n} + \sum_a\left(p_{a,n,t}^{discharge} - p_{a,n,t}^{charge}\right) + P_{n,t}^{unserved} + \sum_{k/=n} p_{kn,t} - \Delta Load_{n,t}^{up} + \Delta Load_{n,t}^{down} = D_{n,t} \quad \text{(eq. 2)}$$

Flow constraint: The value of the flow is limited by the maximum capacity of the line, whose value will depend on the technical, thermal and service safety limits. As for now, flow limits are imposed symmetrically in both directions.

$$-\overline{p_{kn}} \leq p_{kn,t} \leq \overline{p_{kn}} \qquad \text{(eq. 3)}$$

Reserves: After a contingency, the power system must continue operating. Against that, the ISO will take corrective and preventive actions to meet the load requirement. An example of these actions is the reserve capability of the system.

- *Fast reserve:* It is used when the system has an unexpected loss of a generation unit or load. The value of fast reserve for all system will be equal to the size of the largest generation unit of the system.

$$fRes_t^{system} = P^{largest\ unit} \qquad \text{(eq. 4)}$$

On other, each generation unit contributes with a specific amount for fast reserve, characterized by a factor $\eta_{j,n}^f$ according to the type of technology of the unit.

$$fRes_t^{system} \leq \sum_{j,n} \eta_{j,n}^f fRes_{j,n,t} \qquad \text{(eq. 5)}$$

- *Operational reserves:* It corrects the forecast mistakes on an hourly basis, given by variable renewable units and load. The value of the operational reserves for all systems will be given by a percentage $\alpha^{VR} = 5\%$ of dispatched power from variable renewable units and by a percentage $\alpha^{Load} = 3\%$ of the real load in hour t

$$oRes_t^{system} = \alpha^{VR} \sum_{(j\, \in\, VR),n} P_{j,n,t} + \alpha^{Load} \sum_n\left(D_{t,n} + \Delta Load_{n,t}^{up} - \Delta Load_{n,t}^{down}\right) \qquad \text{(eq. 6)}$$

Kindred to fast reserve, each generation unit will contribute an amount of operational reserve to the system. This contribution will be determined by the technology type by the factor $\eta_{j,n}^o$.

$$oRes_t^{system} \leq \sum_{j,n} \eta_{j,n}^o oRes_{j,n,t} \qquad \text{(eq. 7)}$$

Thermic and hydroelectric technical limits: The sum of the power generated, the operational and fast reserve amount of the unit, shall be equal to or lower than the installed capacity of the unit.

$$0 \leq P_{j,n,t} + oRes_{j,n,t} + fRes_{j,n,t} \leq \overline{P_{j,n}} (\forall j \in \text{TH}) \qquad \text{(eq. 8)}$$

Technical and resource limits of variable renewable energy: Analogous to thermic and hydroelectric generation, the sum of generated power and the reserve amount, shall be limited by the installed capacity of the unit.

$$P_{j,n,t} + oRes_{j,n,t} + fRes_{j,n,t} \leq \overline{P_{j,n}} (\forall j \in \text{VR}) \qquad \text{(eq. 9)}$$

However, in this case, with wind and photovoltaics generators, the installed capacity will be constrained by the availability of the natural resource.

$$P_{j,n,t} + oRes_{j,n,t} + fRes_{j,n,t} \leq \overline{P_{j,n}} Profile_{j,n,t} (\forall j \in \text{VR}) \qquad \text{(eq. 10)}$$

Hydroelectric resource limit: The power generated by each hydroelectric plant in the system shall depend on the turbinated flow $q_{h,t}^{turbinated}$ associated with a particular dam and its production coefficient or efficiency k_h.

$$P_{h,t} = k_h q_{h,t}^{turbinated} \qquad \text{(eq. 11)}$$

Energy balance of the dam: The value of $q_{h,t}^{in}$ shall depend on the location of the irrigation intake.

$$V_{h,t+1} = V_{h,t} + \left(q_{h,t}^{in} - q_{h,t}^{out}\right) 3600 \Delta t \qquad \text{(eq. 12)}$$

$$q_{h,t}^{out} = q_{h,t}^{turb} + q_{h,t}^{spill} \qquad \text{(eq. 13)}$$

If the irrigation intake is upstream, the irrigation $w_{h,t}$ shall affect the inflow to the dam $q_{h,t}^{in}$.

$q_{h,t}^{in} = inflow - w_{h,t}$ (eq. 14)

On other hand, when the irrigation intake is upstream and the irrigation $w_{h,t}$ is not rival to the hydroelectricity, the value of $q_{h,t}^{in}$ shall be equal to the natural inflow. Also, the irrigation shall reconcile water usage with hydroelectricity, where $q_{h,t}^{r}$ is the difference between the discharge waterflow from dam $q_{h,t}^{out}$and the irrigation supplied $w_{h,t}$.

$q_{h,t}^{out} = q_{h,t}^{r} + w_{h,t}$ (eq. 15)

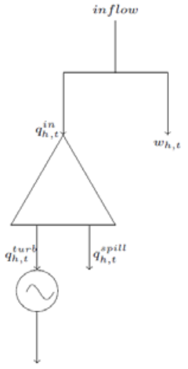


Fig. 1 Upstream Irrigation Intake

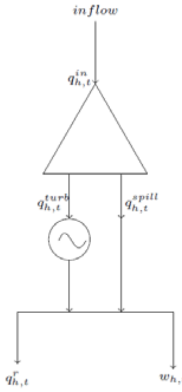


Fig. 2 Downstream Irrigation Intake

Dam level: The dam state is constrained by its minimum and maximum capacity, given by physical and operational limits.

$\underline{V_h} \le V_{h,t} \le \overline{V_h}$ (eq. 16)

Irrigation requirement: At first, the irrigation decision is strictly limited by the seasonal profile of irrigation requirements. However, due to the limitation given by the temporal disaggregation of the irrigation demand, where the whole season has an economic sense, the decision made in the period *t* shall not be independent of the decision made in the period *t+1*, since the decision is not only economical, but also shall meet the crop physiology. Hence, a restriction to the variation in irrigation between two consecutive months is proposed, thus capturing the temporary coupling and consistency with the profile of the season.

Additionally, a flexibility parameter $\alpha^w$is considered to determine the way irrigation is supplied along the season, i.e. the magnitude of how much of the irrigation unmet in the previous month *t-1* can be recovered in month *t*, without affecting the physiology of the crop.

- *Months of increasing requirements*
  $0 \le w_{h*,t+1} - w_{h*,t} \le \overline{w_{h*,t+1}} - \overline{w_{h*,t}} + \alpha^w \overline{w_{h*,t}} (t = month)$ (eq. 17)
- *Months of decreasing requirements*
  $\overline{w_{h*,t+1}} - \overline{w_{h*,t}} - \alpha^w \overline{w_{h*,t}} \le w_{h*,t+1} - w_{h*,t} \le \alpha^w \overline{w_{h*,t}} (t = month)$ (eq. 18)

Where is the sum of the contributions of different dams *h* to the basin *h* *:

$w_{h*,t} = \sum_h w_{h,t}$ (eq. 19)

Battery Energy Storage System constraints:

- *Charge and discharge capacity:* The power of charging (removed from the network) and discharging (injected into the network) shall be limited by the maximum battery capacity $P_{a,n}^{max}$. Illustratively, the binary variable $b_{a,n,t}^{dis}$ is used to ensure that the battery is exclusively in charging or discharging mode and not both simultaneously.

  $p_{a,n,t}^{discharge} \le b_{a,n,t}^{dis} P_{a,n}^{max}$ (eq. 20)
  $p_{a,n,t}^{charge} \le (1 - b_{a,n,t}^{dis}) P_{a,n}^{max}$ (eq. 21)

- *Energy stored:* Analogous to the border constraints of the dam, the battery shall have a minimum and maximum state of charge.

  $stored_{a,n}^{min} \leq stored_{a,n,t} \leq stored_{a,n}^{max}$ (eq. 22)

- *Energy balance*: The state of charge of the energy storage is coupled over time, so that the state of charge $stored_{a,n,t+1}$ will be determined by the state of charge in the period t, plus the stored energy $\eta_{charge} p_{a,n,t}^{charge}$, less the discharged energy $1/\eta_{discharge} p_{a,n,t}^{discharge}$. Note that losses due to conversion systems are considered.

  $stored_{a,n,t+1} = stored_{a,n,t} + \left(\eta_{charge} p_{a,n,t}^{charge} - 1/\eta_{discharge} p_{a,n,t}^{discharge}\right)\Delta t$ (eq. 23)

Demand side management (DSM): DSM shall be understood as the load answer to several system situations. For example, DSM may reduce electricity consumption in peaking hours or increase it in low load hours. The important thing is that the total load will not change, so that the net changed load in the month is zero.

$\sum_{\text{month}} \Delta Load_{n,t}^{up} = \sum_{\text{month}} \Delta Load_{n,t}^{down}$ (eq. 24)

On other, hourly load change shall be limited by a percentage β_{down} or β_{up} of the original load.

$\Delta Load_{n,t}^{down} \leq \beta_{down} Load_{n,t}$ or $\Delta Load_{n,t}^{up} \leq \beta_{up} Load_{n,t}$ (eq. 25)

3. Estimation of unmet irrigation cost

In order to integrate irrigation into the co-optimization model, it is necessary to know the variable cost due to the unmet supply of total irrigation requirement. It should be noted that the dimensions of food safety were not considered in the calculation of this parameter.

One of the most used methods to obtain irrigation demand curves is the Positive Mathematical Programming (PMP) (Howitt 1995), which is focused on characterizing the crops of a given basin with its costs and benefits in a determined season. On the other hand, in order to calculate the monthly requirements for irrigation water using the FAO methodology, it is necessary to know the available water in form of rainfall, soil moisture, etc., in addition to the physiological processes of the crop and weather conditions (FAO-AQUASTAT).

As a result, given the geographical scale considered in this research and the lack of official data about agricultural water resources from some countries, the execution of the above methodology becomes complex. For this reason, a methodology based on the curves obtained through PMP is proposed, in order to estimate the economic impact of agriculture irrigation in each country of the region.

In this way, in order to estimate the unmet irrigation cost and the monthly irrigation requirement of each country, the following data, obtained from the FAO database (FAO-AQUASTAT), is used in the proposed methodology:

- Net production value of the different agricultural crops.
- Annual water withdrawn by agriculture.
- Area actually irrigated.
- Harvested area.
- Crop irrigation calendars by country.

3.1 Irrigation Demand Function

Under the assumption that the unmet irrigation/benefit curves obtained through PMP are quadratic (Rojas 2018, Howitt 1995), the procedure to estimate the irrigation demand function by country is shown in Fig. 3 and is detailed below.

- Given the total area harvested (A_h), the total area cropping from irrigated crops (A_{hi}) and the total net production value of the country (NPV_{total}), the net value corresponding to the area harvested irrigated (NPV_i) is calculated according to the equation 26. The main assumption is that the production yield of the irrigated area is two times the yield of the non-irrigated area (FAO 2011), and the non-irrigated area corresponds to $\overline{A_{hi}} = A_h - A_{hi}$.

  $NPV_i = \frac{A_{hi}}{0.5 \cdot \overline{A_{hi}} + A_{hi}} \cdot NPV_{total}$ (eq. 26)

  This value is considered as the maximum net benefit ($B_{max} = NPV_i$) for the maximum flow of irrigation demand (Q_{max}), derived from the available value of water withdrawn annually by agriculture. In this case, it is assumed that in the year of registration there was no irrigation deficit. Because the demand curve is quadratically shaped, as shown in Fig. 3(a), the parameters that characterize it can be calculated as:

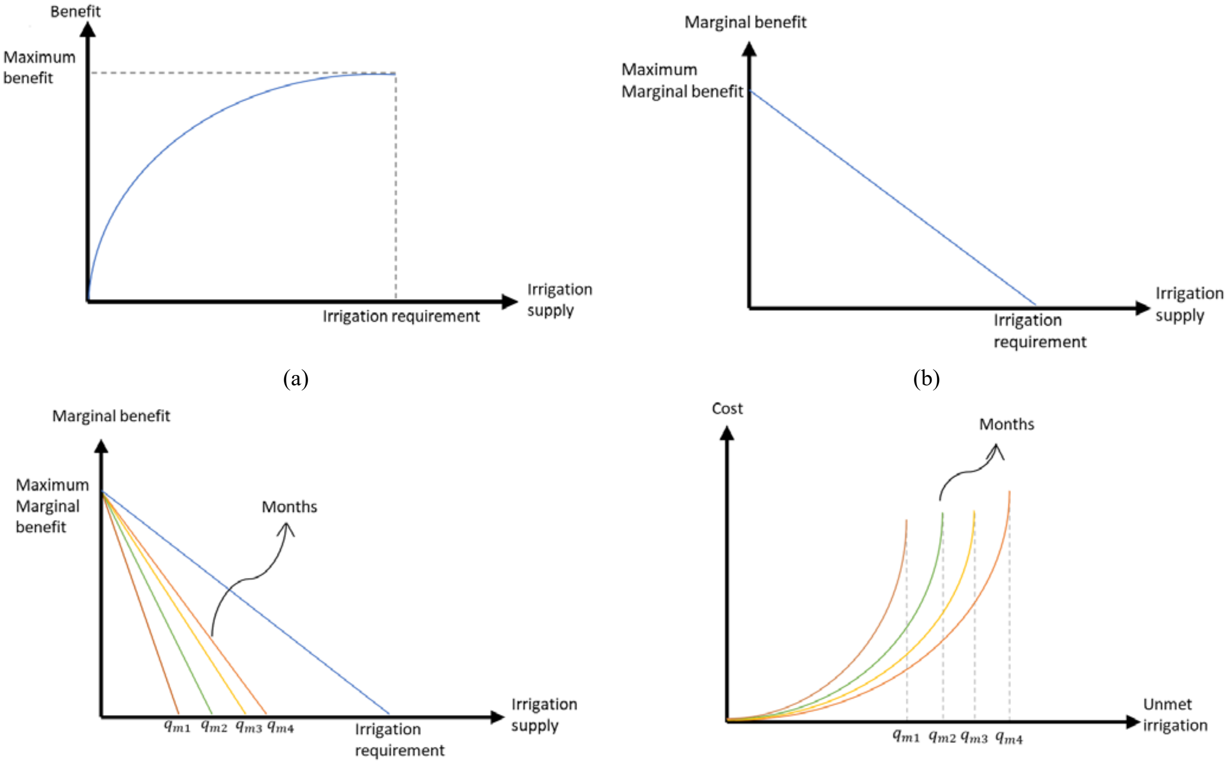
Be a benefit curve based on the irrigation flow supplied, in the form:

$$B(Q) = aQ^2 + bQ + c \qquad \text{(eq. 27)}$$

With the assumptions, the parameters that characterize the function can be obtained, such as:

$$a = -\frac{B_{max}}{Q_{max}}, \quad b = 2\frac{B_{max}}{Q_{max}}, c = 0 \qquad \text{(eq. 28)}$$

- Once the irrigation supplied/benefit curve is known, the irrigation supplied/marginal-benefit curve can be obtained from its derivative, as shown in Fig. 3(b).
- Once the monthly requirement has been calculated, the irrigation supplied/marginal-benefit curve can be disaggregated under the assumption of equi-marginality, which considers that *"the increase in profit produced by the increase of 1 % of the irrigation inflow supplied for every month, is equivalent to the increase in profit produced by the increase of 1 % of the irrigation inflow supplied in the whole season"* (Toro 2017)(Fig. 3(c))
- Given the irrigation supplied/marginal-benefit curves for each month, functions are integrated from right to left in order to obtain the unmet irrigation/cost curves (Fig. 3(d)).



(a) (b)

(c) (d)

Fig. 3 Estimation of irrigation demand curves

In order to calculate the monthly irrigation requirements, it is assumed that the total area actually irrigated (A_{ai}) corresponds to the total water withdrawn by agriculture (Q_{max}). Given that, the water requirement per crop (Q_c) will be assumed proportional to its actually irrigated area (A_{aic}) as shown in the equation 29. It shall not be considered that some crops are more water-intensive than others.

$$Q_c = \frac{A_{aic}}{A_{ai}} Q_{max} \qquad \text{(eq. 29)}$$

Finally, regarding the monthly disaggregation of the annual water requirement of each crop, it shall be assumed that the monthly water requirement of the crop ($Q_{c-month}$) is proportional to its crop coefficient ($K_{c-month}$) according to its growth stage (equation 30). Since there are 4 stages of growth (FAO-AQUASTAT) per season, the irrigation season is divided into 4 and in this way, the related coefficient is assigned.

$$Q_c \propto \sum_{month=1}^{12} K_{c-month} \cdot Q_{c-month} \qquad \text{(eq. 30)}$$

4. Generation and transmission planning data

Two planning scenarios are considered, with a large proportion of the international interconnection simulated from the database of the project "Grid of the Future - Development of a Clean and Sustainable Grid in Latin America" of the Inter-American Development Bank (Paredes 2017) extended to 2042. This exercise was computed with Plexos software.

Planning is carried out with a duration curve that considers 6 monthly blocks over the entire study horizon as a mechanism of computational simplification, given the size of the system. The implemented scenarios have the following considerations:

- Business as Usual (BAU): Considers adequacy constraints for each country, with percentages indicated in Tab. 1.
- Solar: In this case, adequacy constraints for each country are not considered and the objective is to reach 100 GW of solar generation by 2040.

Tab. 1 Adequacy constraints for each country.

Countries	Adequacy [%]
Argentina	17
Bolivia	40
Brazil	40
Belize	12
Chile	40
Colombia	37.7
Costa Rica	40
Ecuador	17.7
El Salvador	40
French Guiana	40

Countries	Adequacy [%]
Guatemala	40
Guyana	40
Honduras	40
Mexico	40
Nicaragua	40
Panama	40
Peru	28.8
Suriname	40
Uruguay	40
Venezuela	40

It is worth mentioning that only the results obtained for the year 2040 were used in this study, in order to capture the dynamics and coupling between the electrical power systems and the use of the water resources in 2040, a strategic year according to climate change mitigation policies and according projections.

The installed capacity per scenario is shown in Fig. 4.

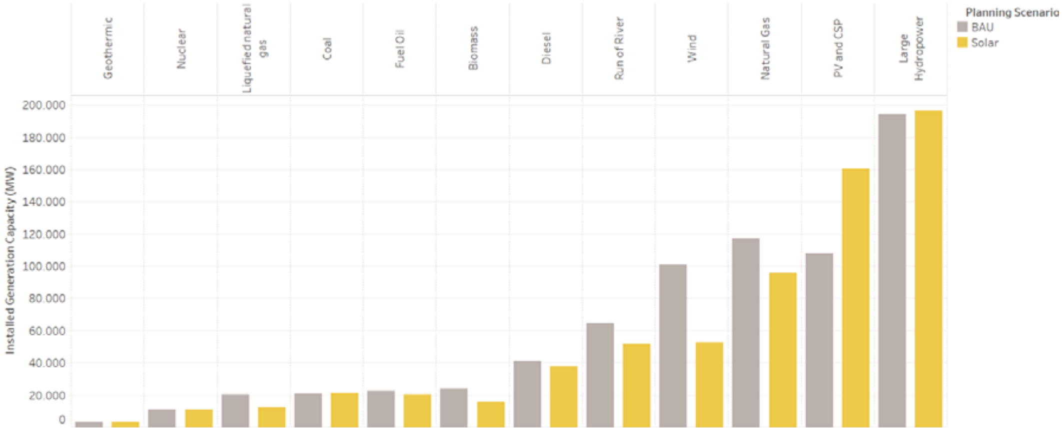
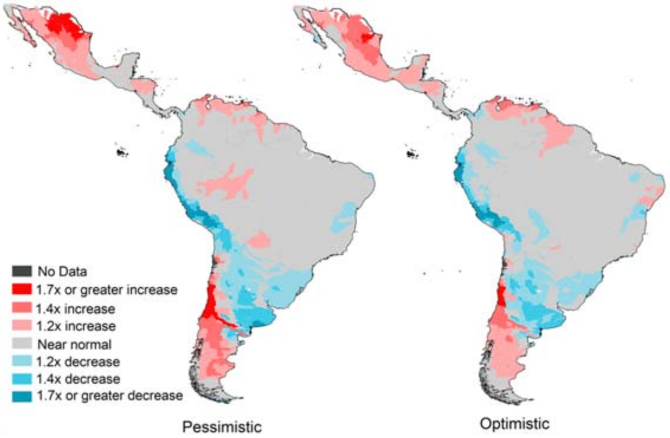


Fig. 4 Installed Capacity by Planning Scenario

5. Climate Change Scenarios

In order to study the impact of climate change in the year 2040, the "water supply" indicator from Luck et al.



(2015) was used (Fig. *6*). This indicator is the projected change in total blue water (renewable surface water) for three combinations of climates (RCP4.5/RCP8.5) and socio-economic scenarios (SSP2/SSP3). Pessimistic (SSP3-RCP 8.5) and optimistic (SSP2-RCP 4.5) scenarios were used in this study.

Fig. 5 Agricultural area actually irrigated in LATAM

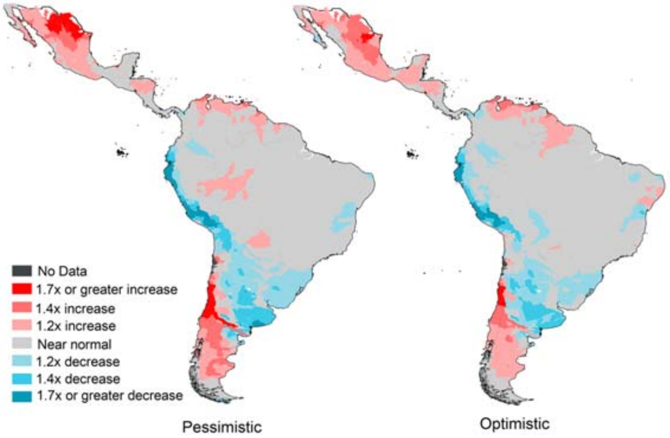


Fig. 6 Projected Change in Water Supply, to 2040

6. Implementation and Results

With the purpose of showing the impact of climate change and water consumption in agriculture behind several scenarios and sensitivities while knowing the possible impacts of the joint management of mentioned resources, a proposed co-optimization model is applied to the case of LATAM interconnection for year 2040 in order to quantify the impact of a larger development of solar energy in Chile, in the context of regional and sectorial energy integration. The model was implemented on Google Cloud Virtual Machine, 12 cores and 52 GB RAM, programmed in Julia and solved using CPLEX 12.8. Feasibility and optimality tolerance were set equal to 10^{-6}, the default value.

The use of scenarios to analyze the impacts of the different input parameters of the model and its interrelations seeks to represent decisions and/or states of the system in the year 2040 and to be able to analyze how the model responses to these changes through the sensibilization of certain variables. Fig. 7 shows an overview of the scenario building procedure.

In this way, different scenarios will be characterized by a specific set of parameters such as the location of irrigation intakes, the level of flexibility and cost assigned to irrigation requirements, presence of demand-side management and changes in water availability in different geographical zones given by climate change effects (see Fig. 8).

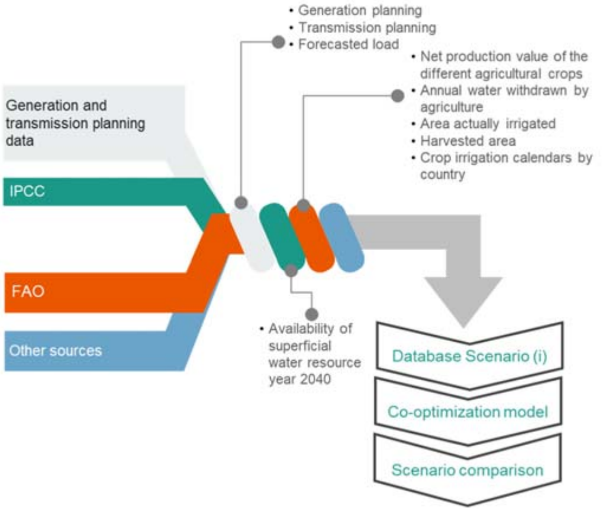


Fig. 7 Methodology Study Case

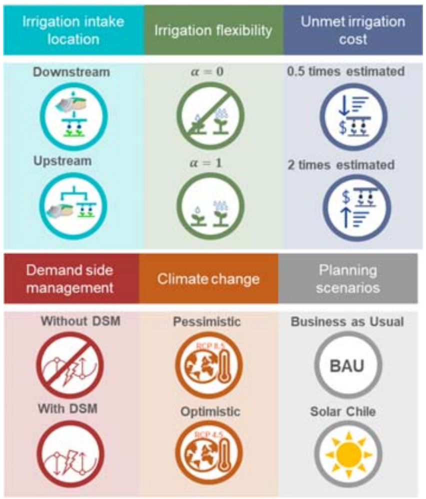
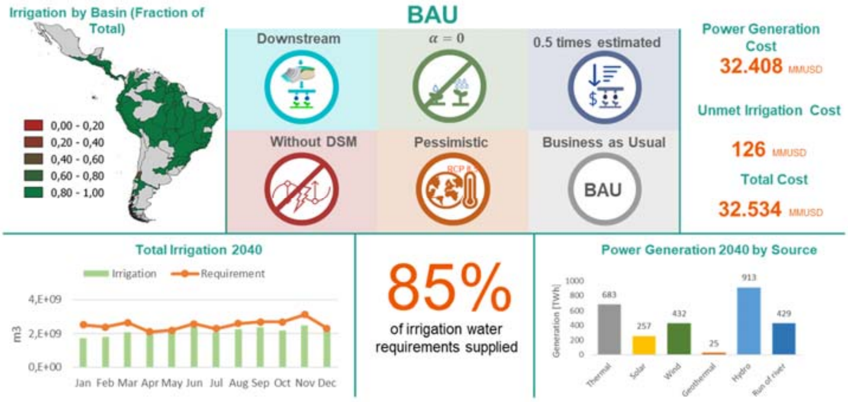


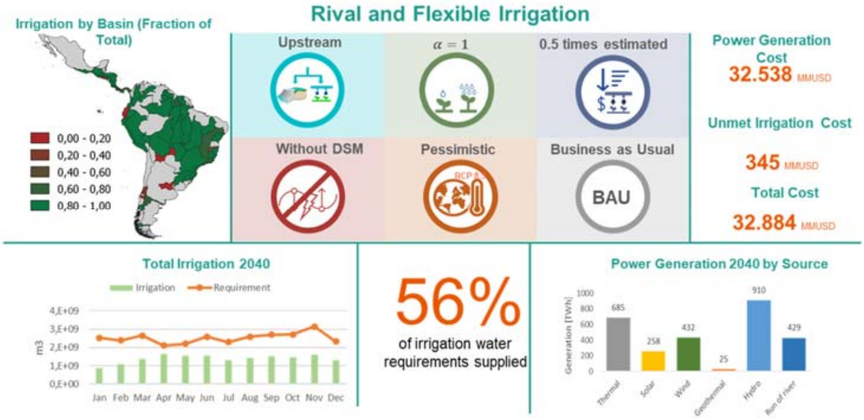
Fig. 8 Scenario Parameters

The following figures summarize the results of four specific scenarios, attempting to show the main tradeoffs observed based on the main indicators (Energy mix, costs, and irrigation supply).

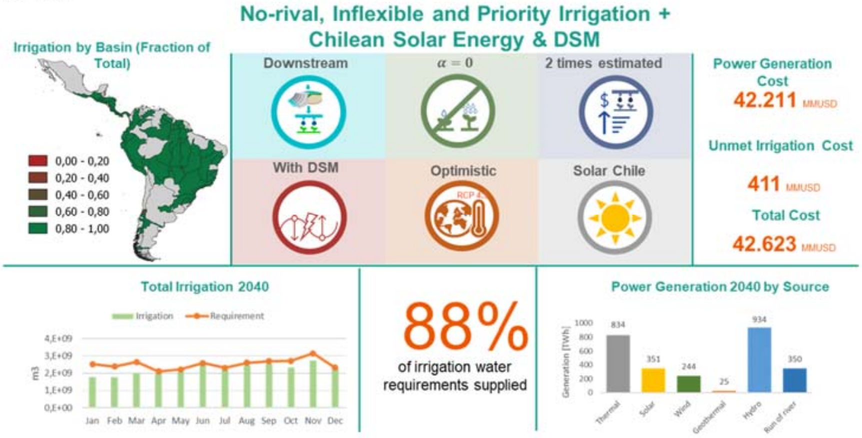
1) BAU would be a good scenario if it does not promote the rivalry between hydroelectricity and irrigation, for example through the downstream location of the intake. In this case the solar penetration corresponds to 15% of the installed capacity.



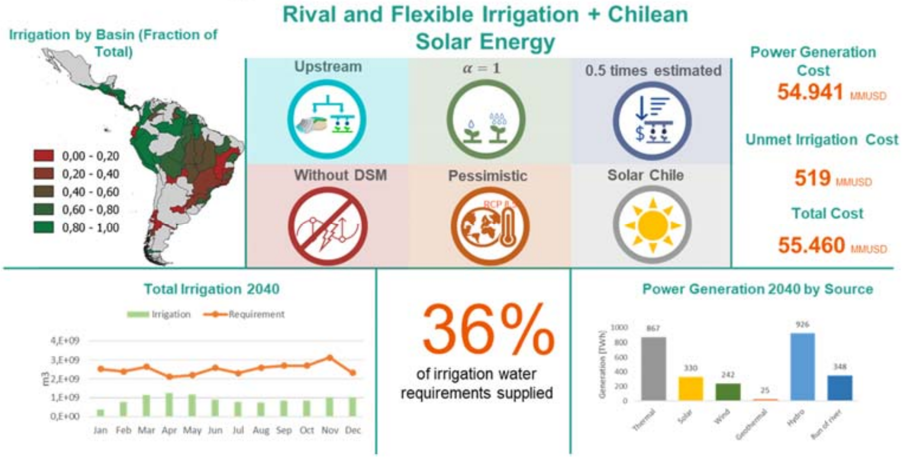
2) The upstream location of the intake in this scenario and the flexibility of irrigation, are partially responsible for a 30% decrease in irrigation compared to BAU. Solar energy generation is not affected by the location of the intake.



3) No rivalry and inflexible irrigation plus demand-side management, results in a high water supply in a solar scenario. In this case, the solar capacity resulting from the planning exercise corresponds to 24%. It is important to note that short-term operational constraints inhibit full deployment of solar energy which promotes higher operational costs.



4) If the amount of solar capacity of scenario 3 is maintained, but the rest of the parameters change to a more inflexible situation, a rise of the total cost is observed as well as a high impact in irrigation supply. These results confirm the need of a holistic approach for the study of solar penetration at a LATAM level.



7. Conclusions

The state-of-the-art of models and methodologies to face the challenges stemming from the water-energy nexus, climate change, and population growth is presented. There are no sufficient models able to describe all the interactions of these links.

Also, the proposed co-optimization model is implemented and validated. It addresses the complexity of water availability driven by climate change in the year 2040 for the LATAM region. Additionally, results show the need to incorporate short-term effects in planning exercises.

Co-optimization model results allow to realize that the knowledge of irrigation intakes location intakes with respect to the power plant is a key information for the analysis. When irrigation and hydropower are not rivals, the development of a solar matrix implies an increase in irrigation, promoting food security. A high value of irrigation costs may ensure water requirements for food production, by considering the alternative use of hydro resources. The proposed model also allows for an estimate of the cost of unserved irrigation requirements. The different sensitivities explored in the case study are the basis of a supporting tool for decision-making. Hence, integrating food security parameters into the co-optimization model remains to be a challenge, and future developments shall be focused on safeguarding both, energy and food security.

In summary, an increase in generation costs in the scenario with a larger solar capacity, compared to other scenarios, is due to the fact that although the installed solar capacity is equal to 100 GW in Chile (an increase of 52 GW of total solar capacity in the continent with respect to the BAU scenario), solar generation in Chile has a 64% of curtailments during some time periods, since the planned transmission capacity is not enough to export to other areas of the system large amounts of solar energy from Chile. The latter has the consequence that the maximum planned solar potential cannot be exploited, therefore having to generate it through thermal sources, increasing the generation costs of the system (previously, the other areas of the system had a higher renewable potential, given that the increase in the solar capacity installed in Chile is compensated by installing 48 GW less of wind capacity than in a BAU planning scenario). The reason for this is the way the planning model addresses the solar generation profile (as it simplifies it to 6 blocks per month), giving erratic signals in the planning because short-term effects cannot be visualized. This major finding of the study can explain the origin of the conflicting positions about solar energy penetration expressed by different stakeholders. Global energy planning tools may show an optimistic long-term penetration of solar energy while power system operation specialists will become more sceptic. The proposed approach can bring these two positions together by showing a more realistic global impact regarding solar penetration. In fact, this work also contributes to a conceptual framework that would work as an initial reference to understand the challenges of co-optimization of water, solar energy, and food at regional levels, a topic of increasing relevance in planning analysis.