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Enhancing the large-scale electric power systems to meet future demands considering the sustainable technologies

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C H R O N I C L E

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A B S T R A C T

Electricity systems are currently expanding towards more efficient forms of production. Several expansionary strategies are being developed to cover increases in future electricity demand. Goals such as reducing greenhouse gas emissions, increasing the efficiency of operations, and achieving more equitable participation of the actors in charge of the investments are set. Following this premise, this paper presents a multi-objective model that helps in decision-making on the problem of expanding electricity generation. The model considers more realistic views than other works in the literature. The vast majority of the stakeholders in the studied field are satisfied with the present proposal. Investment costs, greenhouse emissions, and investment contribution rates are considered. Also, the actual procedures of the generation and transmission stages are rigorously studied. This means obtaining solutions that are closer to reality. The case study is the electricity system of Argentina. The results obtained indicate that the recommended solutions are the most convenient from all points of view. They constitute a mix of the generation with renewable and non-renewable technologies. The case study reveals emission reductions of up to 25% and it can be achieved that the most vulnerable social groups do not have to finance future system expansions.

1. Introduction

Subsidies in the energy sector in Argentina have been developed as a form of compensation for the poorest households. This was the result of the great Argentinean crisis of 2001 (Rabobank, 2013). This calamity led to the devaluation of the local currency and the end of the so-called "convertibility" (which established that one Argentine peso was equivalent to one US dollar). The basic idea of these subsidies was to suspend increases in the tariffs of the main energy services (electricity and natural gas supply). The currency devaluation promoted an immediate increase in the cost of providing energy services. The country's economic growth that followed this crisis led to price inflation (Reinhart, Carmen & Savastano, 2003). During the first years of the convertibility crisis, poverty and unemployment levels were increased. As a consequence, the reordering of tariffs was politically unfeasible (Guzowski, 2011). Although at the beginning it was very effective in protecting the economies of households with economic problems, over the years, the amount of money allocated to these subsidies began to represent a significant portion of the State's coffers. Indeed, in 2004 energy subsidies represented 0.2% of GDP, while in 2014 they represented 2.9%. After the change of government (during 2016-2019), there was a reduction in the percentage of subsidies. The evolution of these subsidies is shown in detail in Fig. 1. This subsidy scheme led to a disproportionate increase in energy consumption. As of 2003, there was an increase in the salaries of the population, and the values of the tariffs were "cheap" because they were virtually “frozen” due to the subsidies. This brought several problems (Arze del Granado et al.,

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2012), not only the important expense for the country but also problems in the electricity sector. During that period, companies in the electricity sector worked with low-cost tariffs. This situation caused these companies to be placed in a complex financial situation, which generated disinvestment in the sector (Guzowski, 2011).

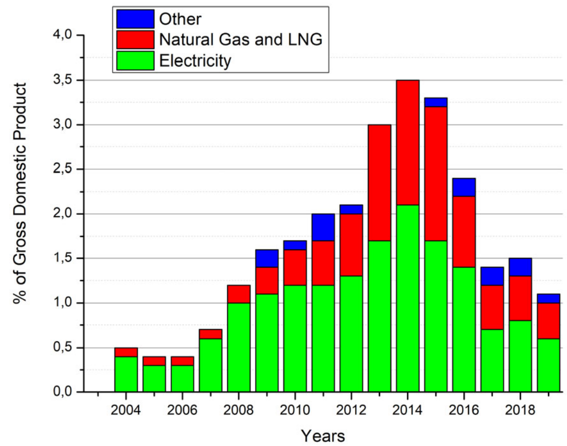

Fig. 1. Subsidies in Argentina during 2003-2019. Based on (Asociación Argentina del Presupuesto, 2015; Lopetegui, 2019)

In the early 1990s, the tariff for energy services had to cover long-term costs (including the profit for the service operator). Moreover, according to (Azpiazu, D., Forcinito, K., & Schorr, 2001), tariff changes were not similar for different types of users. Between 1991 and 1998, the average tariff for electric energy was reduced by 10.9%, but in the residential area, it was reduced by only 8.5%. In contrast, the industrial tariff was reduced by 13.9%. This difference is even more noticeable when comparing the different residential sectors: in high consumption residences, the reduction was 70.4%, while low consumption residences were reduced by only 1.6%. The same trend was observed in the case of natural gas services. When the average increase was 37.3%, the residential tariff increased by 111.8%. By contrast, the large industrial users had an increase of 1.4%. At the end of 2001, with the economic crisis in Argentina, users saw their salary income decrease. Problems such as unemployment, price increases, and devaluation caused the average wage to fall to less than half of a similar wage in 1998 (in dollars) (Groisman, 2012). The percentage of poor households grew since 1995 and reached record levels in 2003 (42.6%). In addition, more than half of the population corresponded to poor households, and they were unable to pay for all public services. Consequently, the effects of the crisis in the energy sectors were important. Subsequently, when the economy started to recover in 2005, the limited generation capacity needed to cover the increased demand. This led to using frequently more expensive machines, thus, increasing thermal generation. This occurred as a consequence of poor policies to increase installed generation capacity in Argentina during the previous years.

During the period 2005-2015 economic subsidies were increased dramatically, mainly destined to the energy sector. They functioned as a disguised wage and consumption lever. Authors such as (Castillo, D., & Szkolnik, 2019) conclude that the State did not focus subsidies particularly on the sectors with the greatest needs. Even more, due to deficient tariff schemes, the electricity was sold very cheap to sectors with important incomes. In 2012, the government decided to implement a tariff increase through the "voluntary waiver", and the removal of subsidies in certain geographical regions. In addition, tariff arrears were produced. The scenario became significantly more complex due to the economic slowdown experienced from that year. With the change of government in Argentina, as of 2016, there was a percentage drop in energy subsidies (concerning GDP). However, the reduction in subsidies, with the subsequent increase in energy tariff, affected all sectors equally. This meant that many residential and productive sectors were not in a position to pay the elevated tariff increases. With the assumption of the new government as of December 2019, the bases for a new tariff scheme and development policies for the energy sector in Argentina have been presented. But in the last year (2020) it was difficult to evaluate these objectives due to the emergencies that have occurred in the country as a result of the pandemic caused by COVID-19. This disease has caused a great impact, not only in the economic and social aspects but has even caused great imbalances in the country's energy system. Besides, new generating technologies must be considered in the country structure (G. Alvarez, 2022).Therefore, the current scenario is complex and its solution requires a combination of social, economic, and technical approaches. As can be deduced from the above, the electricity system requires a large investment to expand its capacity in the upcoming years, considering the expected future increase in demand.

The study of power system expansion, considering new technologies and emissions, has been developed in several works. The authors of (Yang et al., 2008) use a real options approach to evaluate the effects of government climate policy on private investors. In (Bøckman et al., 2008), a method for estimating small hydropower projects is presented. The approach is tested on three Norwegian hydropower projects. The authors of (Lin & Wesseh, 2013) analyze the benefits provided by the electricity tariff in China, for solar PV production. They use a real option pricing approach to approximate the value of this technology, compared to fossil fuel prices. The work of (Boomsma et al., 2012) studies a Nordic case for wind technology installation considering incentives for larger projects and energy certificate trading. In (Zhang et al., 2016), a real model for evaluating renewable energy investment is proposed. It considers PV generation in China including multiple uncertain factors. In (Chen et al., 2021), the authors study the decisions of a monopolistic company investing in the renewable sector using a *cap and trade* method. They conclude that more investment in the renewable sector does not necessarily decrease carbon emissions. Regarding the need for electricity expansion, in (Azam et al., 2021) the authors analyze the relationship between economic growth and the electricity consumption increase.

Regarding the decisions about expanding a system to achieve cleaner production, it is a complex task and includes many aspects that must be carefully considered. Choosing only one point of view for these decisions can be a big mistake. For instance, if the expansion of a type of technology with a lower cost is selected, this expansion can be very dangerous to the environment. On the other hand, if the technology is chosen due to its lower emissions, but its high costs are not considered, the selected option may involve an elevated cost that makes the project unfeasible. For this reason, the literature has studied the multi-objective models, which consider more than one point of view in decision-making processes. Although most works consider up to two objective models, in which one is to reduce the cost of operation and the other to reduce emissions, it is possible to find some approaches where the problem of investing in cleaner production is addressed. In this regard, (Heinen et al., 2016) studies the feasibility of thermal and wind technologies considering the investment costs in the objective function, besides fuel consumptions and carbon emission, are considered by weighting values. In (Fazlollahi et al., 2012), a multi-objective optimization model implementing an evolutionary algorithm is presented. The model is decomposed into a master and a slave stage to reduce the computational effort. The authors of (Cayir Ervural et al., 2018) present an energy planning model under close-to-reality constraints. The objectives are weighted by applying an analytical hierarchy process. In (Aquila et al., 2020), the investments in wind generation are analyzed considering the uncertainty.

In this context, the present work proposes the following contributions:

- To design and implement a multi-objective optimization model that allows improving and expanding the energy system, considering all the actors involved: investments and system operators. The current state of the power system will be considered, as well as the projected future demands according to forecasts.

- Evaluate the stability of new generation technologies. For this purpose, environmental factors will be considered to reduce the production of greenhouse gases.

-To study how the introduction of new renewable energies affects the traditional systems.

- Establish an adequate balance about how these expansions will be financed between residential and commercial users, the government, and private investments.

The rest of the paper is organized as follows: Section 2 introduces the mathematical models to be solved, Section 3 describes the case study, Section 4 discusses the results and Section 5 summarizes the conclusions.

2. Mathematical model

This section presents the formulation of the three models to be solved using multi-objective optimization.

2.1 Expansion system cost

The objective function (1) is the minimization of the cost of expanding the electricity system (EC) by increasing installed capacity. It is the sum of the variable representing the increased capacity (σ_x , in MW) affected by the installation cost of the corresponding generation technology (δ_x , in USD/MW). This model considers all possible sources. The above indexes correspond to the different types of sources considered: (g) natural gas-fired thermal, (dg) non-natural gas-fired thermal, (h) hydro, (n) nuclear, (w) wind (pv), solar PV and (or) other minor renewables. In addition, x is the index for each unit and X is the total number of units to be installed.

$$\min CA = \sum_{x}^{X} \left(\sigma_x^g \delta_x^g + \sigma_x^{dg} \delta_x^{dg} + \sigma_x^h \delta_x^h + \sigma_x^n \delta_x^n + \sigma_x^w \delta_x^w + \sigma_x^{pv} \delta_x^{pv} + \sigma_x^{or} \delta_x^{or} \right) \quad (1)$$

Constraint (2) establishes the maximum installed capacity of a given unit. It considers that in certain regions it is not feasible to increase the installed capacity of a unit. This occurs, for instance, in the case of wind farms, which should not be installed where there is low wind activity. The same reasoning applies to photovoltaic plants where there are not many clear sunny days. In these cases, the constant $\sigma_{x,t}^{max}$ (in MW) will be equal to 0. This constraint must be extended to all generation sources considered.

$$0 \leq \sigma_x \leq \sigma_x^{max} \qquad , x = 1, \ldots, X \quad (2)$$

In addition, there are specific constraints belonging to each type of generation technology. These constraints should be included because they affect the efficiency of the selected units for the expansion proposals. Otherwise, a possible solution could include units that have low installation costs, but high operating costs, and this is contrary to the premise of efficient system operation. Such constraints are detailed in (Gonzalo Alvarez, 2020a).

To model electricity transmission, the DC flow model is adopted, which is described in (Stott et al., 2009). This model obtains feasible solutions with low computational effort, in comparison with other nonlinear models (such as the AC model (Overbye et al., 2004)). The electricity transmission is modeled in (4). The variable $e_{ba_i,ba_o,t}$ is the power flow (in MW) on a line that is connected by the input (ba_i) and output (ba_o) buses. In addition, $\theta_{ba_i,t} - \theta_{ba_o,t}$ is the difference of the voltage angles between the connected buses (in rad), and $Reac_{ba_i,ba_o}$ is the reactance (constant, in p.u.) between the connected buses.

$$e_{ba_i,ba_o,t} = \frac{\theta_{ba_i,t} - \theta_{ba_o,t}}{Reac_{ba_i,ba_o}}, \quad t = 1, \dots, T \tag{4}$$

The balance of power flows per bus is modeled in (5). The constraint determines that the sum of the generated power ($\sigma_{i,bu,t}$ per current units and $\sigma_{x,bu,t}$ for power generated per future units) and the transmitted power (input power $e_{ba_i=ba,ba_o,t}$ minus output power $e_{ba_i,ba_{o=ba},t}$) must be equal to the stored power ($SP_{ba,t}$), the outgoing transmitted power ($e_{ba_i,ba_o=ba,t}$), and the demand ($ca_{ba,t}$).

$$\sum_{i}^{I} \sigma_{i,bu,t} + \sum_{x}^{X} \sigma_{x,bu,t} + e_{ba_i=ba,ba_o,t} - e_{ba_i,ba_o=ba,t} = \sum_{c=1}^{C} ca_{ba,t} + SP_{ba,t}$$
$$t = 1, \dots, T; ba = 1, .., BA \tag{5}$$

2.2 Environmental costs

The pollution-related to electricity generation considered in this work is based on greenhouse gas emissions. Several authors conclude that the most convenient form to study pollution emission lies in the life cycle of generation units (Pereira & Posen, 2020). Emission rates are particular to each type of generation technology and are influenced by geographical factors (Weisser, 2007). The definition of the life cycle is important in determining emission ratios. For example, the emission ratios of photovoltaic units have decreased in the last decade, due to advances in their manufacturing process. The plants with the highest emission ratios are coal-fired plants. On the other hand, natural gas power plants have lower emission values within fossil sources.

The objective function (6) considers the sum of the production of each unit affected by the emission factor. This factor establishes the tons of CO_2 emitted for each MWh. Several formulations and approaches address emissions in nuclear (Sovacool, 2008), thermal (Martínez & Eliceche, 2009), solar photovoltaic and wind (Nugent & Sovacool, 2014), and hydroelectric units (Rasanen et al., 2018). The formulation implemented in this work to determine emissions has two main concepts. The first one seeks to relate the operation of the system to the emission that these sources produce. The second concept is to get the mathematical model according to the MILP formulation (Mixed Integer Linear Programming) to respond to a large-scale system, without applying external techniques that may exclude the global optimum of the search (such as decomposition techniques). Therefore, it presents the objective function that minimizes the emission of each of the mentioned sources. In this objective function, e_x is the unit emission constant (in tons of CO_2 equiv/MW).

$$\min CO_2\text{em} = \sum_{x=1}^{X} (\sigma_x^g e_x^g + \sigma_x^{dg} e_x^{dg} + \sigma_x^n e_x^n + \sigma_x^w e_x^w + \sigma_x^{pv} e_x^{pv} + \sigma_x^{or} e_x^{or}) \tag{6}$$

2.3 Determination of investments

The objective function (7) implies the minimization of the investment to be made by each of the actors in the system. It considers the investment to be made by each type of user (in USD/MW): residential (iv^r), commercial (iv^c), industrial (iv^{id}) and other users (iv^o). In addition, n_i is a constant of the number of users in each category. In addition to the contribution that users should make, there are two variables representing public investments iv^e (by the government) in USD, and private investments iv^p. This objective function can be reformulated to minimize the contribution of a particular type of actor. For instance, one strategy could be minimizing the investments made by the State. In this case, only the variable iv^e should be minimized, instead of the sum presented in (7). Besides, the variables belonging to users can be decomposed into more categories. For example, within residential users, subgroups can be established according to the amount of kWh consumed monthly. The same applies to commercial and industrial users. For this paper, only one category has been included for each type of user, to simplify the reading of the mathematical model and the presentation of results in the case study.

$$\min inv = iv^r n^r + iv^c n^c + iv^{id} n^{id} + iv^o n^o + iv^e + iv^p \tag{7}$$

Constraint (8) establishes that the sum of the investments of all the actors mentioned above must be equal to the system expansion cost mentioned in (1). Due to this constraint, the objective function (7) can be rewritten by minimizing only one (or several) of the six variables presented in that sum, and still maintain consistency among the different models of an objective presented.

$$iv^r n^r + iv^c n^c + iv^{id} n^{id} + iv^o n^o + iv^e + iv^p = CA \tag{8}$$

Constraint (9) determines the limits on the contributions that can be made by each of the actors. This is important because for instance, due to the economy, residential users in the lowest categories cannot exceed a certain contribution limit. Given their complex social situation, an increase in their tariffs may be confiscatory and impossible to pay.

$$iv_{min} \leq iv \quad \leq iv_{max} \qquad , i = 1, \ldots, I \tag{9}$$

2.4 Multi-objective model

In recent years, the concept of *Pareto optimality* has begun to gain importance in multi-objective problems, as opposed to the classical concept of optimality (Ji et al., 2017). When a single-objective solution is considered, the solutions of other objectives may get worse. Multi-objective approaches are usually classified in the literature into two categories: preference and generative. The first group includes most of the published approaches. With these methods, a singular objective receives more attention than the others. The disadvantage of these methods is the lack of objectivity that could be produced. The *generative* methods, which are included in the second group, include the called *epsilon constraint approaches* (ECA, (Esmaili et al., 2011)) and *weighting approaches* ((Breen et al., 2019)). ECA approaches consist of a single main function and the rest of objectives are formulated as constraints. In contrast, weighting approaches formulate the objective function by mixing the single objective functions using weighted factors. The ECA method is particularly useful to solving the multi-objective system expansion problem. The process of exploring the entire feasible region can be a difficult task. Therefore, the use of the payoff table formed from the solution of the individual problems will be adopted. The performance level of the method depends on the range of values to evaluate each single objective. In addition, the lexicographic technique will be applied to reach the solutions. With this technique, the preferences for solving are strengthened by ordering the objective functions based on their position or implication, better than if weights are associated (Arora, 2012).

Considering the above statements, the ECA method is chosen to solve the problem of the present work. A complete description of the method can be found in (Mavrotas, 2009). The best values are easily achievable by considering the optimum of simple optimization. The formulation of the ECA method is presented as follows (based on (Osorio Muriel et al., 2014)). The formulation presented in (10) represents an objective function formed by the first objective function $f_1(s)$, and the remaining objective functions are represented as constraints affected by an epsilon value. Where *s* the set of possible solutions and *FR* is the feasible region of solutions.

$$\begin{aligned} &\min f(s) = f_1(s) \\ &\quad\text{s.t.} \\ &f_2(s) \geq \varepsilon_2 \\ &f_3(s) \geq \varepsilon_3 \\ &s \in FR \end{aligned} \tag{10}$$

Within the ECA methods, lexicographic optimization is applied (Zykina, 2004). It constitutes a sequence of objective functions that optimize the first objective function, then, the second objective function, and so on. Lexicographic optimization can be summarized as follows:

- The first objective function (main objective) is optimized and z_1^* is obtained.
- The second objective function is optimized while including the constraint $f_1 = z_1^*$ in the formulation and z_2^* is obtained.
- When the third simple objective function is optimized, the constraints $f_1 = z_1^*$ and $f_2 = z_2^*$ are considered.

The processes are repeated until all the objective functions are optimized.

3. Case of study

The Argentine Electric System or simply SADI (Sistema Argentino de Interconexión) is formed by nine electric regions: Buenos Aires (BAS), Centro (CEN), Comahue (COM), Cuyo (CUY), Litoral (LIT), Gran Buenos Aires (GBA), Northeast (NEA), Northwest (NOA) and Patagonia (PAT). More than half of the electricity demand belongs to Buenos Aires and Greater Buenos Aires. The matrix of energy generation sources is composed of fossil fuels (60.2%), hydroelectric energy (22.9%), nuclear generation (8.1%), and the rest of renewables (8.8%). The fossil fuel matrix is dominated by natural gas (89.8%), diesel (5.5%), fuel oil (3.0%), and coal (1.7%). Within the renewable matrix are wind (73%), photovoltaic (10.7%), hydroelectric < 50 MW (9.7%), biomass (4.4%), and biogas (2.2%). Fig. 2 shows the single-line diagram of the SADI with the 500 kV transmission grid.

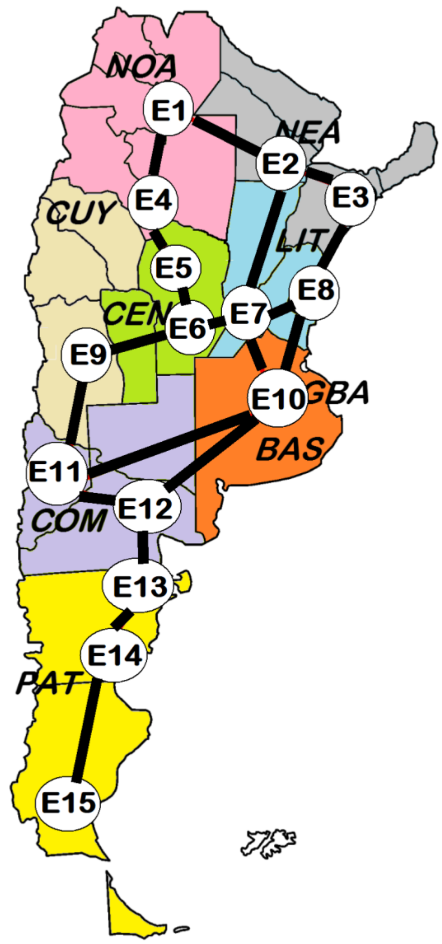

Fig. 2. SADI one-line diagram with the 500 kV transmission grid

The SADI is organized based on the interactions among Generation Companies (GENCOs), Transmission Company (TRANSCO), Distribution Companies (DISCOs), and the Independent System Operator (ISO). Each of the nine regions admits only one DISCO (a regulated monopoly). In relation to power transmission, there is only one TRANSCO (TRANSENER) that operates more than 10,000 km of 500 kV lines. Argentina is highly dependent on fossil fuels for energy consumption and generation. In addition, there is a lack of ability to compensate for the demand for electricity, especially in times of high consumption. This can lead to major failures of power grids. There are several types of energy storage systems. However, pumped storage systems are the type with the largest global capacity. In 2017, the global installed capacity of pumped storage capacity is about 153 GW. There are over 400 pumped storage power plants in operation (or under construction) in the world. Regarding the operation of these plants in Argentina, in (Gonzalo Alvarez, 2020b) a mathematical model is developed that considers a larger number of breakpoints for the representation of the operating curves of these units. The paper also considers as a case study the two pumping plants in Argentina (Los Reyunos and Rio Grande). These plants are also considered in this case study.

The current status of the SADI has been discussed in (Gonzalo Alvarez, 2020a). The main challenges and current problems are:

- The impact that an increase in tariffs has on an important part of the population. These are the main source of financing the system's infrastructure (and expansion). Therefore, the limit between the users' contributive capacity and the quality of the system is very complex.
- It is necessary to diversify the energy matrix in order to avoid excessive reliance on fossil fuels. The new generating technologies may be strategic due to the availability of several natural sources in the country.

- Only 29% of the bill paid by the consumer corresponds to the DISCO (called VAD) which is used to pay salaries, maintenance, investment, etc. Around 41% of the bill corresponds to the payment to the wholesale makers and the remaining 30% are direct taxes. The total taxes of the service represent 46% of the total bill.
- With the supposed future scenario (inflationary expectations for 2021 between 35% and 50%), conversations regarding tariff updates have begun.
- It will be difficult for companies, consumers, and the State to support the high inflationary variations. On the one hand, distribution and generation companies have cost increases without transferring these variations to consumers. Besides, consumers will have to face higher tariffs without having increased salaries. And if the freezing tariffs continue and the origin of the problem is not directly attacked, the State will have to continue to maintain the subsidy policy increasing the deficit.

The information on SADI implemented in this work is based on (Gonzalo Alvarez, 2020a). Regarding CO_2 emissions, the data used are based on the report presented in (Krey V., 2014). The report presents emission values for different electricity supply technologies (in gCO_2eq/kWh). It considers not only direct emissions, but also infrastructure and supply chain emissions, and other factors such as biogenic CO_2 emissions. Information regarding the number of users in the country are the following (based on (Secretaría de Energía de la República Argentina, 2021)): 13,382,765 residential, 1,518,956 commercial, 201,128 industrial, 401,287 in the "other" category.

Regarding the investments, there are two predominant factors to be taken into account: the timeliness of data and the influence of regional factors. The most up-to-date information on investment costs is important because new technologies are reducing their manufacturing cost. For example, the investment cost of photovoltaic technology has decreased over the last 10 years. The distinction between regions is necessary because the costs could be different between regions. For instance, the North American region costs are lower than the Latin American region. Based on the above, the investment costs included in this work can be found in (Comisión Nacional de Energía, 2020). This report is recent and is developed by a Latin American country neighboring the case study, which shares many economic and geographical factors with Argentina.

4. Results

The model is solved using the GAMS software (Bussieck & Meeraus, 2004), with the linear solver Gurobi, on a Pavilion DV-7 notebook with AMD A6-3400M APU processor and 8 GB of RAM. The programming horizon is one year, with a period of one day. To obtain the payoff table (necessary to start the multi-objective optimization) the objective functions described in Sections 2.1, 2.1, and 2.1 are minimized individually (relaxing the variables belonging to the other objectives). As the investment costs are considered the core of this work, the objective function (1) will be considered as f_1 , the objective function (4) will be set as f_2 , while the objective function (5) is the function f_3 , as described in the formulation of (10).

A 30% increase in demand is assumed, which represents an increase in demand as estimated for the next 10 years in the system. The model solved is composed of 132,233 simple equations, 144,632 continuous variables, and 21,170 binary variables. Moreover, each iteration is solved in about 19.2 seconds. Fig. 3 shows the resolution of the problem from three points of view for 10 possible solutions. The horizontal axis of the graph shows the annual CO_2 emissions that would be produced by the future power system. In turn, the vertical axis shows the investments required to install the generating park (it means installing the new plants). A first hypothesis that can be made, based on the figure, indicates that as lower emissions are required, the installation cost increases considerably.

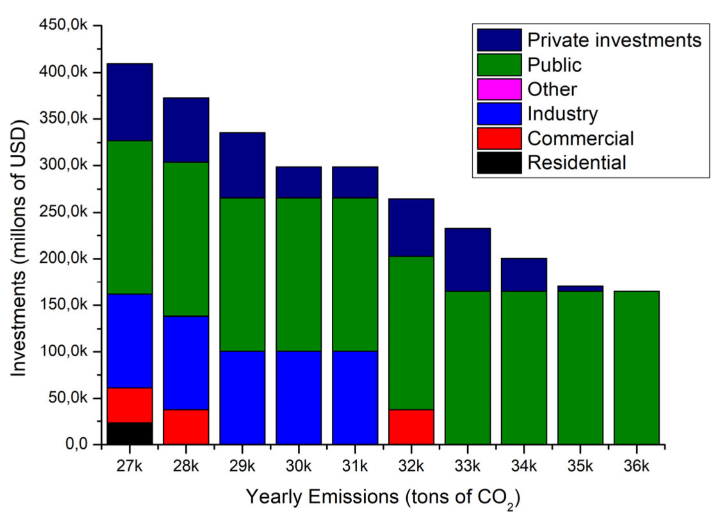

Fig. 3. Profile of the sources of investment required for system expansion

In addition, the figure shows the profile of the investments required by each of the types of inverters that exist in this problem, according to the constraints (7-9). The limits for each type of inverter are as follows: iv^{r}_{max}= 1,500 USD, iv^{c}_{max} = 25,000 USD, iv^{id}_{max} = 500,000 USD, iv^{o}_{max} = 2,500 USD, iv^{e}_{max} = 165 billion USD, and iv^{p}_{max} = 85 billion USD. It should be remembered that in the case of $iv^{r}, iv^{c}, iv^{id}, iv^{o}$, to obtain the total contribution shown in the figure one must multiply the individual contribution of each user by the total number of users. The figure shows the possible results for 10 configurations. Solutions are ordered in the figure from the one that generates the least annual emissions (27,000 tons of CO_2) to the one that generates the most annual emissions (36,000 tons of CO_2). These are the emissions of the whole generating park. The recommended solution is the one with an annual emissions value of 31,000 tons of CO_2. This recommendation is based on the configuration of contributions that it presents. For the social details described in Section 2.2, a solution where residential users do not have to directly finance the expansion of the system is of interest (given the current economic problems prevailing in the country). The current economic situation already has many difficulties, in terms of how the majority of the population has to face the current costs of the system (without considering expansion). The generation profile for the recommended solution is shown in Fig. 4. This profile distinguishes the type of technology used, and also distinguishes between units that are already operating and those that would be installed in the recommended solution (for these units the word "ext." is added in the references in the figure). The average daily generation of the technologies already installed is composed as follows: nuclear 42.12 GWh, hydroelectric 228.6 GWh, non-natural gas thermal 0, natural gas thermal 139 GWh, wind 0.52 GWh, and solar PV 4.58 GWh. In addition, the generation with the assumed future units consists of nuclear 12.4 GWh, hydro 35.3 GWh, wind 0.65 GWh, and solar PV 4.68 GWh.

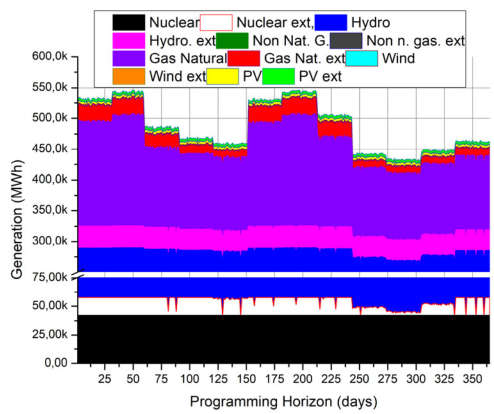

Fig. 4. Generation profile for the recommended solution

Regarding the electricity transmission under the new configuration, Fig. 5 shows a transmission profile for six of the main lines of the 500 kV system. As can be seen, the current configuration of the Argentine System can support the increase of transmitted flows for future demand. This is because the transmission system has been constantly expanded in recent years. Lines L2 and L6 handle power peaks of more than 8000 MW per day (during certain periods of the year, as shown in the figure).

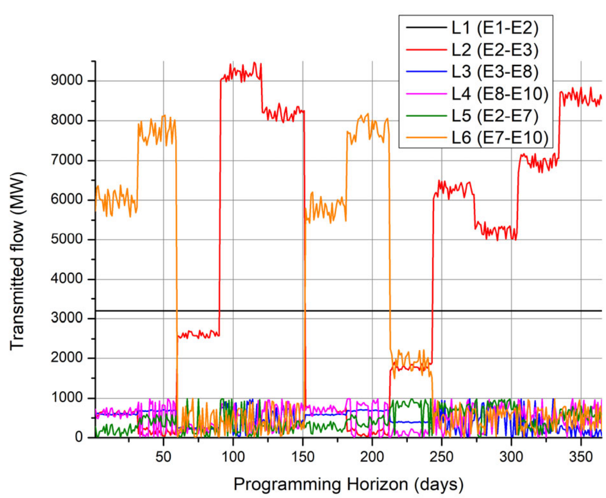

Fig. 5. Transmission profile for the recommended solution

5. Conclusions

This paper introduces a new multi-objective approach that helps with investment decisions for the expansion of electricity systems, in terms of considering more sustainable productions. The proposed model considers several aspects that are not often included in the literature, such as the different actors when investing in new generation technologies. One of the main differences with other proposals is that the present paper includes the most widespread generation sources in the world (not only renewable technologies). This means obtaining more realistic solutions. In several countries, investments in conventional fossil fuel technologies could be more convenient, due to the combination of several factors. This is the situation of the considered test case. The present formulation can offer as many possible solutions as preferred (considering the corresponding computational needed to solve more iterations). To prove the effectiveness of the proposed model, a real case is analyzed, which is the Argentine Electricity System (SADI). In this case, different system configurations are analyzed. The scenario studied considers an increase in demand forecast for the next 10 years, the recommended investment option implies a 14% reduction in emissions (compared with the feasible solution with the lowest value). This solution implies the installation of units from renewable sources but also traditional technologies (non-renewable). It is important to note that the model does not suggest the installation of wind and solar generators to large extent due to their costs (compared with cheaper sources such as natural gas or hydro). It is important to mention that this condition is a particular situation of the country, based on the costs and resources analyzed. The options chosen bring mutual benefits for all actors of the system: entities in charge of emissions control, investor groups, consumers of the system, and state participation. The model also analyzes real system operation situations, considering a predecessor model that schedules electricity generation and transmission throughout the country. This results in solutions closer to real situations, compared to other approaches. Furthermore, although this work is developed to analyze the energy situation in Argentina, it can be extended to the cases of other countries, due to the versatility of its formulation.

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