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Optimization tools for the operational dispatch of power generation systems to reduce diesel fuel consumption

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Abstract:

Bolivia, despite being a relatively small country, has several small cities far away for the National Interconnected System. For this reason, these cities have Isolated Systems and almost 70% of their installed power are generated through thermoelectric plants, which ended up being a problem because of the high diesel fuel consumption. The diesel fuel supply in Bolivia is not guaranteed because the country depends on importation at very high prices. In this sense, this study intends to reduce the diesel consumption of the isolated power generation systems in Bolivia using an operational dispatch optimization model. First, there were chosen 3 Isolated systems in Bolivia, the Cobija Hybrid System, the Sena Hybrid System and the Gonzalo Moreno System. The latter is a purely thermal system, while the other two are hybrid systems (thermal and photovoltaic plants). Then, a comprehensive analysis of the power demand and supply has been completed for the three cases. Subsequently, an optimization model has been developed using the software Matlab and its complementary package knows as the Optimization Tool Box. Using this model, a comparison has been made between the operational dispatch of the energy system with and without optimization. The results indicate that it would be possible to save 2211 L/day, 182 L/day and 73 L/day of diesel consumption with an optimization process for the Cobija Hybrid System, the Sena Hybrid System and the Gonzalo Moreno Systems, respectively. These diesel fuel savings would represent more than 1.31 MM$ in money savings for the Bolivian Government.

Keywords: Optimization, hybrid energy system, diesel fuel consumption.

1. Introduction

In Bolivia, a country in South America, the largest population is concentrated in its main cities. The energy supply in the main cities is guaranteed because these cities are part of the National Interconnected System (NIS). The NIS connects 8 out of 9 departments in Bolivia, the only department that is not part of the NIS is Pando, which is located in the northern part of Bolivia in the middle of the Amazon forest.

Considering that there is a Department of Bolivia that is not connected to the NIS, the cities of this department have Isolated Systems (IS). Most of the isolated systems are thermoelectric plants that work with diesel fuel due to the difficulty of the natural gas transportation to these cities since most of them are in the middle of the Amazon Forest. The Isolated Systems in Bolivia are Cobija, El Sena, Gonzalo Moreno, Baures and Guayaramerin. Some of them are hybrid energy systems, which combines two or more types of energy generation.

According to [1], hybrid generation systems are a viable solution for electricity supplying especially when there are access difficulties to the location or when the city is too far away of the National Interconnected System. In the region, there are some examples of hybrid generation systems. For example, there is a photovoltaic-diesel hybrid system in Campinas, Amazonas – Brazil with a power capacity of 99.2 kW. In Rondonia - Brazil, the hybrid system of Araras presents an installed diesel power of 162 kW and 20.48 kW of power in the photovoltaic plant. On the other hand, there is also examples of hybrid generation system between wind generation and diesel thermoelectric generation like the energy system in Vila de Praia Grande, Brazil. In Bolivia, the hybrid systems are Cobija and El Sena, which are photovoltaic-diesel hybrid systems. Cobija has an installed capacity of 24.16 MW in diesel and 5.10 MW in photovoltaic, and El Sena has a total installed capacity of 4.62 MW [2].

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As mentioned before, the hybrid systems in Bolivia use diesel as the source of energy. For this reason, the consumption of diesel in Bolivia in general has increased a lot the last decades. Figure 1 shows that the diesel consumption in the isolated systems System has been increasing rapidly the last ten years. In 2021, the isolated systems have expended approximately 57,800 m3 of diesel fuel.

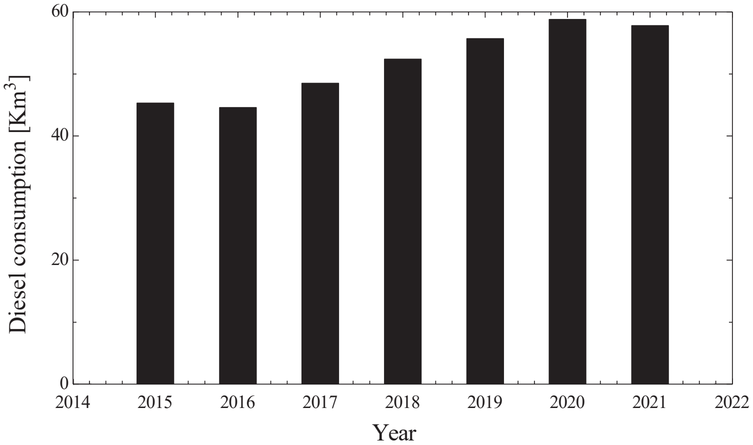

Figure. 1. Isolated systems diesel consumption in Bolivia per year.

Unfortunately, Bolivia does not produce diesel fuel. Hence, the country depends on the importation of this fuel and, therefore, on the international prices of the diesel. Figure 2 shows that the diesel in 2022 was approximately 10.1 Bs per liter (1.45 $ per liter). It's also worth to mention that the price of diesel is increasing since 2020 (8.6 Bs/liter), so it´s possible that the next years the price of the diesel is going to be even more than 10.1 Bs per liter.

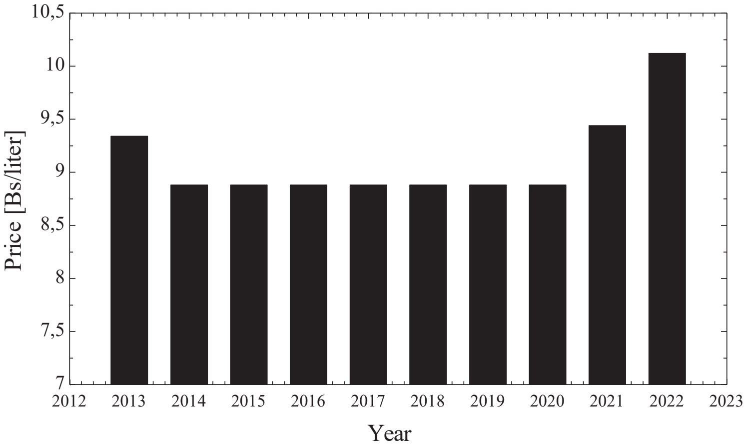

Figure. 2. Diesel price evolution [2], [3], [4].

On the other hand, the installed power of the Isolated Systems reached a value of 216.71 MW, of which 67.54% was thermally generated. So, Bolivia needs approximately 57800 m3/year of diesel fuel, which represents 84.5 MM$/year in order to keep the isolated systems working, and consequently, providing electric energy to a lot of small cities in the country.

Sempértegui-Tapia et al. [5] presented a case of study for the optimization of the Cobija Hybrid System. The authors recommended some changes in the operational dispatch of the energy system which allowed them to save 2622 L/day of diesel consumption. In this paper, we intend to further the mentioned study by including the analysis of 3 out of 5 isolated systems in the country. The Cobija Hybrid System will be analysed again, with updated data. Also, El Sena Hybrid System and the purely thermal Gonzalo Moreno System are going to be optimized. This way, the proposed optimization tool proposed by [5] is going to be validated and assessed using it for three different energy systems, which have very unique characteristics like number of generating units, installed power, load and demand factors, etc.

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2. Mathematical model of the operational dispatch optimization

The mathematical model of the optimal operational dispatch consists on an objective function (OF), equality constraints (EC) and inequality constraints (IC), as shown in Eq. (1).

$$\text{Minimize} \rightarrow \ \mathbf{OF} \text{ subject to} \begin{cases} EC \\ IC \end{cases} \tag{1}$$

The modelling requires the objective function, which is formed by the energy consumption equations of the generating units; the equality constraints of the energy balance between demand and supply of the generating units and the inequality constraints that limit the power delivery of the generating units. Thus, taking into account that the energy consumption equations are second degree polynomial, the problem results in a non-linear program. Considering the characteristics of the "n" generating units in the IS (energy consumption equation and on-site effective power) and the isolated system type (hybrid or purely thermal), the mathematical model of the optimal operational dispatch is shown in Eq. (2).

$$\mathrm{minf(P)} = \sum_{\mathrm{i}=1}^{n} \mathrm{C_i} \text{ subject to} \begin{cases} \mathrm{d} - \sum_{\mathrm{i}=1}^{n} \mathrm{p_i} - \mathrm{p_s} = 0 \\ 0 \leq \mathrm{p_1} \leq \mathrm{p_{e1}} \\ \vdots \\ 0 \leq \mathrm{p}_n \leq \mathrm{p_{en}} \end{cases} \tag{2}$$

Equation (2) defines the operational dispatch problem. In order to solve this problem, the objective function has to be defined first and then the interior point algorithm will be used.

2.1. Objective function

The behaviour of a generating unit is described by the overall ratio of the heat input to the thermal unit in Btu/h vs the power output in MW. These behaviour is mathematically modelled by a second degree polynomial equation:

$$\mathrm{C_i} = \mathrm{a_i P_i^2} + \mathrm{b_i P_i} + \mathrm{c_i} \tag{3}$$

Therefore, the objective function will be composed by the sum of "n" energy consumption equations, one for each generating unit present in the isolated system.

2.2. Interior point algorithm

The interior point algorithm is normally used in nonlinear programming due to the speed of convergence and the ease of handling the inequality constraints. Besides, this method has advantages with quadratic-type constraints.

In this method, the approximation process starts from an initial point inside the plausible zone, moving internally until the global optimum point is found. In the case of the operational dispatch in thermal generation systems, 2nd order polynomial equations are presented to form the objective function and to determine the constraints. In other words, this method works with the Lagrange function modified by the inequality constraints present, the Karush Kuhn Tucker conditions and finally uses Newton Raphson to approximate the problem to an optimal solution.

Matlab and the Optimization Toolbox add-on provide a number of algorithms for solving a wide range of optimization problems. The optimal operational dispatch problem converges using the *fmincon* routine, that operates the interior point algorithm.

2.3. Multidimensional matrix

As mentioned before, the interior point algorithm is an iterative tool that starts from an initial point and travels through the interior of the solution space considering the constraints of the problem. In this way, the interior point algorithm must solve the following multidimensional matrix:

$$\begin{bmatrix} \mathrm{W_K} & \nabla\mathrm{R(P)} & -\mathrm{I} \\ \nabla\mathrm{R(P)^T} & 0 & 0 \\ \mathrm{Z} & 0 & \mathrm{P} \end{bmatrix} \begin{bmatrix} \mathrm{d_P} \\ \mathrm{d_\lambda} \\ \mathrm{d_z} \end{bmatrix} = - \begin{bmatrix} (\nabla\mathrm{f(P)} - \lambda\nabla\mathrm{R(P)} - \mathrm{z}) \\ \mathrm{R(P)} \\ (\mathrm{zPe} - \mu\mathrm{e}) \end{bmatrix} \tag{5}$$

It should be noted that the system has the form Ax=b, with the difference that the components of the matrix A and b are also matrices that will change size according to the dimension of the problem and its restrictions. The iterations will stop when d_p^{n-1}-d_p^{n} approaches 0.

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For more detailed information about the mathematical model for this optimization dispatch problem, Sempértegui-Tapia et al. [5] should be consulted.

3. Optimization dispatch solver

The operational dispatch solver (ODIS) has 11 graphic windows elaborated with the help of Guide Matlab. These windows also have programming code where all the instruction for the correct operation of the tool are written. This way, this operational dispatch solver is very friendly with the user even more considering the graphical interface.

One of the main features of the program are the ability to work with a hybrid system and also with a thermal system. Also, the program allows the user to stablish a maintenance plan for the generating units and also allows the user to modify the maximum power delivery for the process.

On the other hand, the program provides the user with a power table that describes the optimum economic dispatch profile. More importantly, the solution includes an hourly consumption graphic that could be displayed globally for the isolated system of more detailed, considering all the components of the system.

The input and output parameters for the optimization dispatch solver are discussed next.

3.1. Input parameters

The parameters needed in order to optimize an energy system are:

1. Energy consumption equation: The behavior of a generating unit is considered through the general ratio between the heat input and the power output.
2. Characteristic days of demand: the user can select the characteristic days of demand of the energy system.
3. Available solar power: It refers to the photovoltaic solar power installed, which interacts with the thermal power plant.
4. Maintenance program: This program provides the information about the periods of time where some generating units will not be available.
5. List of available units: Determines the list of available generating unit to be considered to perform the optimization.
6. Effective power: The status condition of each generating unit is determine don site.
7. Rotating reserve: Corresponds to the percentage of the demand that is predicted to absorb the variation of the distribution system. The user can select this value up to 15%.

3.2. Output parameters

The first output parameter is the optimized power of the generating units. The tool also calculates the diesel consumption in liters and the hourly operating cost of the thermoelectric plant. With these output parameters, the program presents different kinds of figures to the user in the graphical interface.

4. Optimization tools applied to real hybrid power generation systems

The optimization tools were applied to three different isolated systems in Bolivia. Two of them are hybrid system (thermal and solar) and one of them is purely thermal.

4.1. General description of the isolated systems

4.1.1. Cobija Hybrid System (CHS)

The CHS is located in the Northern part of Bolivia, more specifically in the department of Pando. Also, it is one of the oldest and largest isolated systems in the country. Furthermore, is under the management of the National Electricity Company (ENDE) since 1990. This company not only supplies electricity to the city of Cobija, but also, to the towns that are within its operational area. Currently the Cobija System is a Hybrid System; due to the combination of two generation technologies; a diesel thermoelectric plant and a photovoltaic solar plant. Figure 3 shows a complete scheme of the CHS illustrating both plants.

The thermoelectric plant has diesel generating units of the Caterpillar brand. Until 2018, this thermoelectric plant had a total of 14 diesel generating units, with an approximate growth in demand of one generating unit per year (approx. 1.4 MW). The electric company ENDE, in order to properly identify the generating units, labelled each generating unit beginning with the code of the pant “BAH” and a numerical value according to the order of commissioning. As observed in the figure, the thermoelectric plant has two voltage levels in generation: 6.6 kV and 0.315 kV. The units that generate in 0.315 kV require a transformer that raises the voltage to 6.6 kV, so that they can be coupled to the 6.6 KV rigid busbar in the electrical substation.

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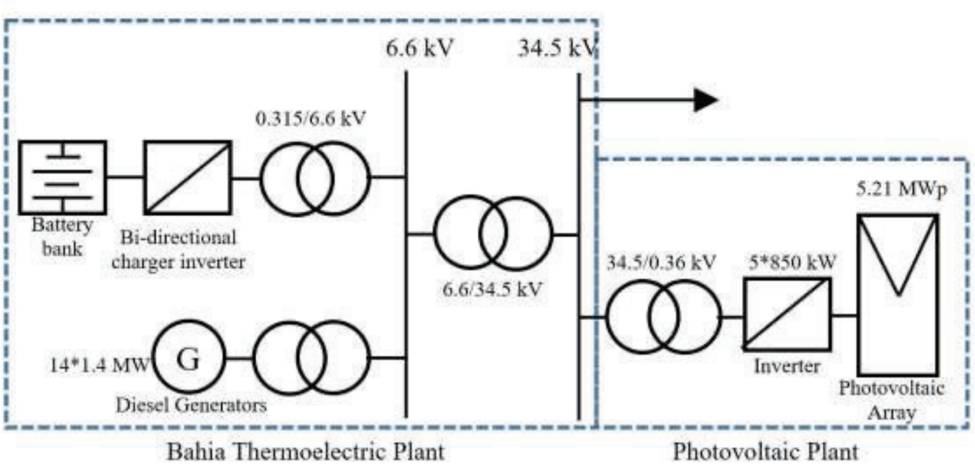

Figure. 3. Scheme of the Cobija Hybrid System.

The photovoltaic plant is comprised of 17,352 solar panels of 300 W. The total installed power is 5.21 MW. It is located about 7 km away from the city. Moreover, it is connected with the BAHÍA thermoelectric plant through a 34.5 KV sub-transmission line that reaches a 34.5 KV flexible bus from the substation (see Figure 3).

Also, a battery bank is located at the thermoelectric plant and uses energy generated by the CATERPILLAR generating units for its own consumption and also constantly supplies the grid. The SAFT brand battery bank is made up of 2 containers with Li-ion batteries.

Table 1 shows the operational limits and the 2nd degree equation of energy consumption for each generating unit of the CHS.

Table 1. Operational limits and 2nd degree equation of energy consumption for each generating unit, CHS.

Generating Unit	Operation limits	a	b	c
BAH01	$P_{01} \leq 1400$	-0.2528	10.05	-0.0092
BAH02	$P_{02} \leq 1600$	-0.1909	10.118	-0.0016
BAH04	$P_{04} \leq 1200$	-0.2435	9.7298	-0.007
BAH05	$P_{05} \leq 1400$	-0.0979	10.5298	-0.0069
BAH06	$P_{06} \leq 1400$	-0.0632	10.2078	-0.005
BAH07	$P_{07} \leq 1400$	-0.27	10.237	-0.0142
BAH08	$P_{08} \leq 1200$	-0.3675	10.005	-0.0063
BAH09	$P_{09} \leq 1400$	-0.3675	10.005	-0.0063
BAH10	$P_{10} \leq 1400$	-0.2835	9.8879	-0.0087
BAH11	$P_{11} \leq 1400$	-0.1	10.423	-0.0007
BAH13	$P_{13} \leq 1400$	-0.4923	10.511	-0.0009
BAH14	$P_{14} \leq 1400$	-0.1472	10.095	-0.0004
BAH15	$P_{15} \leq 1600$	-0.1448	9.96388	-0.004
BAH16	$P_{16} \leq 1600$	-0.1022	9.9368	-0.0061

For more information on the Cobija Hybrid System see Sempértegui-Tapia et al. [5].

4.1.2. Sena Hybrid System (SHS)

The SHS is located in the Sena Municipality of the Madre de Dios Province in the Department of Pando, on the banks of the Manuripi River. This system has 9 generating units; two of them are Scania brand, 2 are CAT brand and 5 VOLVO brand. This system has also a photovoltaic plant of 436 kW of installed power. The configuration of this hybrid system can be observed in Figure 4.

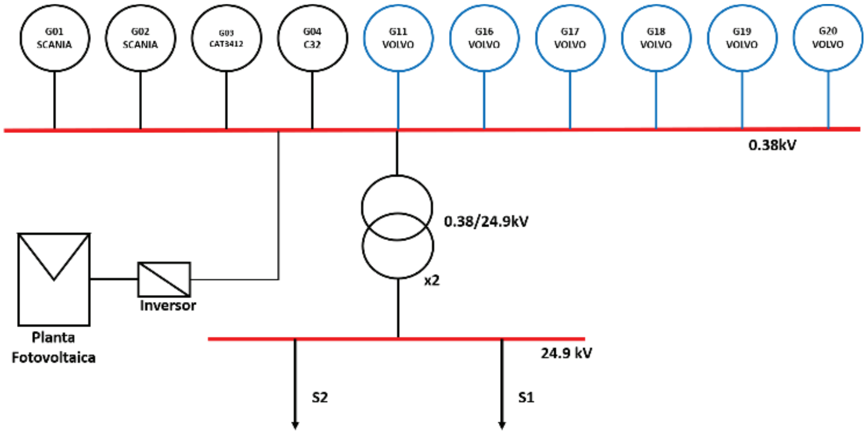

Figure. 4. Scheme of the Sena Hybrid System.

Table 2 shows the operational limits and the 2nd degree equation of energy consumption for each generating unit of the SHS.

Table 2. Operational limits and 2^{nd} degree equation of energy consumption for each generating unit, SHS.

Generating Unit	Operation limits	a	b	c
G01(Scania)	$P_{G01} \leq 350$	-5.8857	11.934	-1.60E-03
G02(Scania)	$P_{G02} \leq 350$	-0.6945	11.577	0.0015
G03(CAT3412)	$P_{G03} \leq 350$	0.2951	11.6	-0.003
G04(C32)	$P_{G04} \leq 500$	0.2951	11.6	-3.00E-03
G11(VOLVO)	$P_{G11} \leq 200$	7.4646	10.783	8.60E-03
G16(VOLVO)	$P_{G16} \leq 200$	1.1231	11.483	1.90E-03
G17(VOLVO)	$P_{G17} \leq 200$	1.1231	11.483	1.90E-03
G18(VOLVO)	$P_{G18} \leq 200$	-2.2623	11.915	-1.10E-02
G19(VOLVO)	$P_{G19} \leq 200$	5.1106	10.646	2.43E-02
G20(VOLVO)	$P_{G20} \leq 200$	0.1113	11.623	-0.0015

4.1.3. Gonzalo Moreno System (GMS)

The GMS is located in the Municipality of Puerto Gonzalo Moreno in the province of Madre de Dios in the Department of Pando. It is responsible of three activities; generation, distribution and commercialization of electric energy. It has a powerhouse of 3 Volvo generating units (see Figure 4).

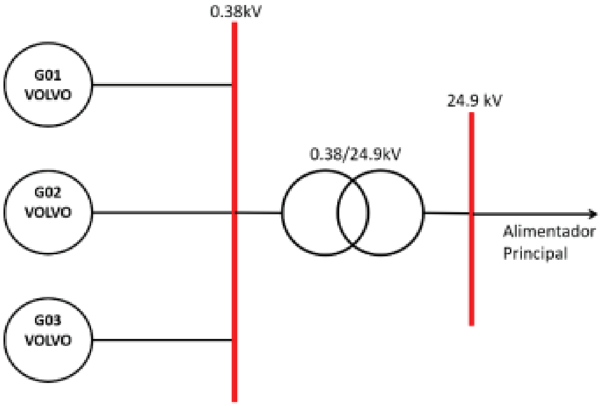

Figure. 5. Scheme of the GMS.

Table 3 shows the operational limits and the 2nd degree equation of energy consumption for each generating unit of the GMS.

Table 3. Operational limits and 2nd degree equation of energy consumption for each generating unit, GMS.

Generating Unit	Operation limits	a	b	c
G01(VOLVO)	$P_{G01}≤200$	-32.805	12.73	-4.00E-05
G02(VOLVO)	$P_{G02}≤200$	-0.357	10.722	0.0049
G03(VOLVO)	$P_{G03}≤200$	0	0	0
G04(VOLVO)	$P_{G04}≤200$	-1.8357	10.661	-4.00E-05
G09(VOLVO)	$P_{G05}≤200$	-3.5981	10.272	0.0002

4.2. Power demand analysis

Electricity demand is distributed by categories, the most important ones for their incidence are: industrial, commercial and residential. But also, there are other categories like public lighting, police, pumps, whose participation are not comparable to the aforementioned.

Typical demand curves have characteristics that differ from one another, a residential curve will rapidly increase its demand in the period from 18 to 21 hours; a commercial curve will slightly increase its demand in the same period; while an industrial curve will not have a noticeable demand between this period.

Figure 6 illustrates the demand of the three energy systems. Gonzalo Moreno is purely residential, Cobija has a demand associated with the commercial sector and Sena shows an intermediate behavior between residential with the commercial sector. Is worth to mention that neither of this cities show an industrial demand.

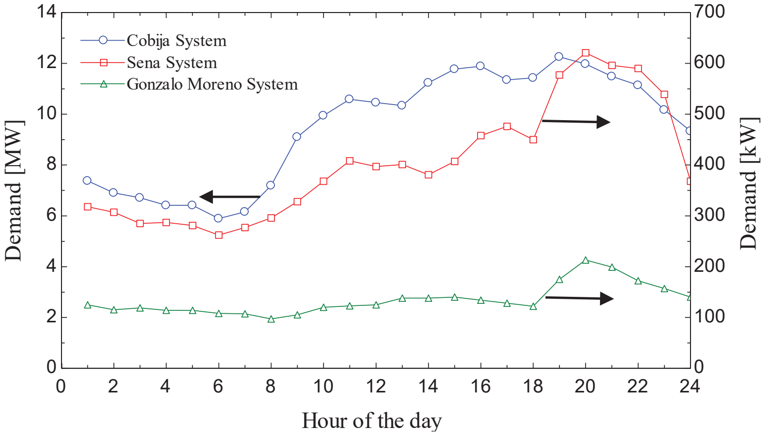

Figure. 6. One-day operational dispatch without optimizing.

To characterize the demand of the energy systems, representative curves were carefully calculated and plotted according to the procedure suggested by [6]. This analysis resulted in a total of 17 representative curves. Eight curves belong to business and non-business days, five curves related to the recorded temperature and four curves for operational events. All the generated curves are summarized in Figure 7 (see [5] for more detailed information).

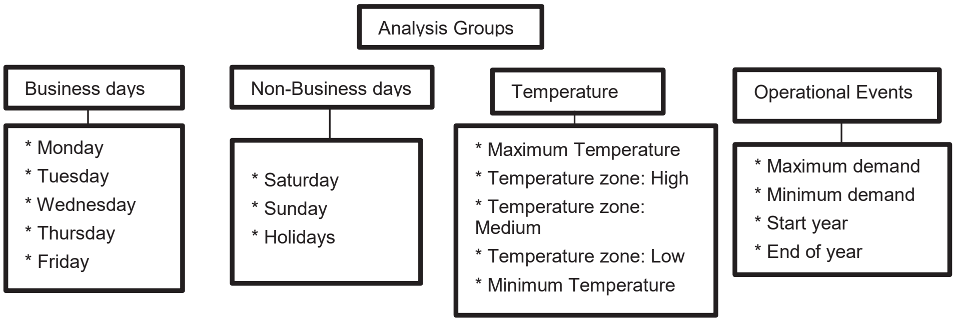

Figure. 7. One-day operational dispatch without optimizing.

4.3. Power supply analysis

Table 4 shows a summary of the important operating data for the three energy systems that are being analyzed.

Table 4. Operating data of the three energy systems.

Operating Data	CHS	SHS	GMS
Energy [MWh]	60160	2824	1019
Diesel consumption [m^3]	15981	878	287
Generating units	14	9	3
Installed thermal power [KW]	19800	2550	600
Photovoltaic panels	17352	1292	0
Installed solar power [KW]	5206	426	0
Maximum demand [KW]	12262	621	213

In order to analyze the power supply of the energy systems, three important variables were calculated for each of them. These performance indicators are the load factor, the demand factor and the specific consumption and can be observed in Figure 8.

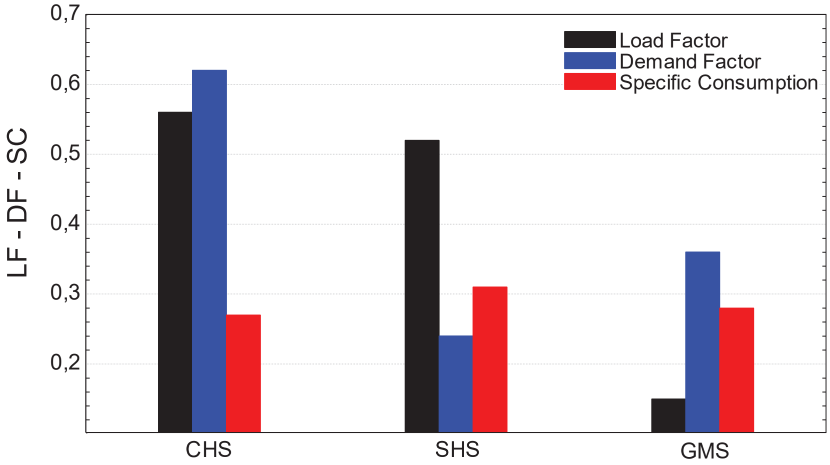

Figure. 8. Performance indicators for the three energy systems.

As it can be observed in the figure, the CHS has a very satisfactory relationship between demand and supply. On the other hand, the SHS has an installed power that exceeds the demand almost four times.

5. Results and discussions

To obtain the results, the three systems were run with the program. All the necessary data, including the demand analysis, operational availability, and others were the input parameters to obtain an optimized energy system. The rotating reserve used for the operation was 10%. Table 5 shows the general results of the optimization model for the three energy systems.

Table 5. Summary of the optimization results.

Indicators	CHS	SHS	GMS
S.C. (Actual) [L/KWh]	0.27	0.31	0.28
S.C. (Optimized) [L/KWh]	0.252	0.287	0.256
Savings [m^3/año]	807	66	27
Savings without subsidizing [KBs/year]	888	73	29
Savings with subsidizing [KBs/year]	8223	677	272

As observed in the table, the optimization results show savings in the fuel consumption for the 3 cases. It can be observed a reduction of the specific consumption for the optimized system compared to the real system. This indicates that the electricity demand could be meet by optimizing the energy resource. In economic terms, it can be observed annual savings of 9172 KBs for the 3 energy systems. More detailed information about each one of the energy systems are discussed below.

5.1. Cobija Hybrid System (CHS)

Figure 9 shows an operational dispatch in a period of 24 hours for the CHS without the use of the optimization program. The shallow area represents the photovoltaic generation, and every other colour in the figure represent one generation unit added to the system. It can be noted that in order to meet the demand, eleven generating units must be working in addition to the photovoltaic plant. These 13 generating units consume 44260 liters of diesel fuel.

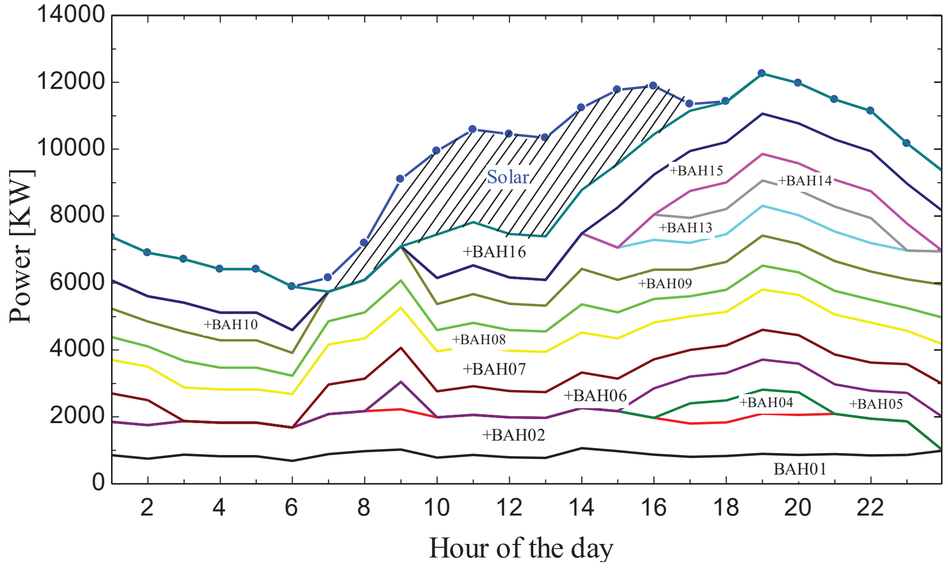

Figure. 9. One-day operational dispatch at the CHS without optimizing.

On the other hand, using the optimization algorithm, it´s possible to reduce the number of generating units dispatched on the same day to 10 (see Figure 10). Also, a better load factor of this equipment is achieved, which is demonstrated by the height of the areas shown by each generating unit. Furthermore, a better distribution of the service of generating units is achieved, minimizing the starts and taking full advantage of the contribution of the photovoltaic solar plant (shallow area). Finally, the CHS with the optimization model needs 42049 liter of diesel consumption, which means 2211 liters of diesel on savings.

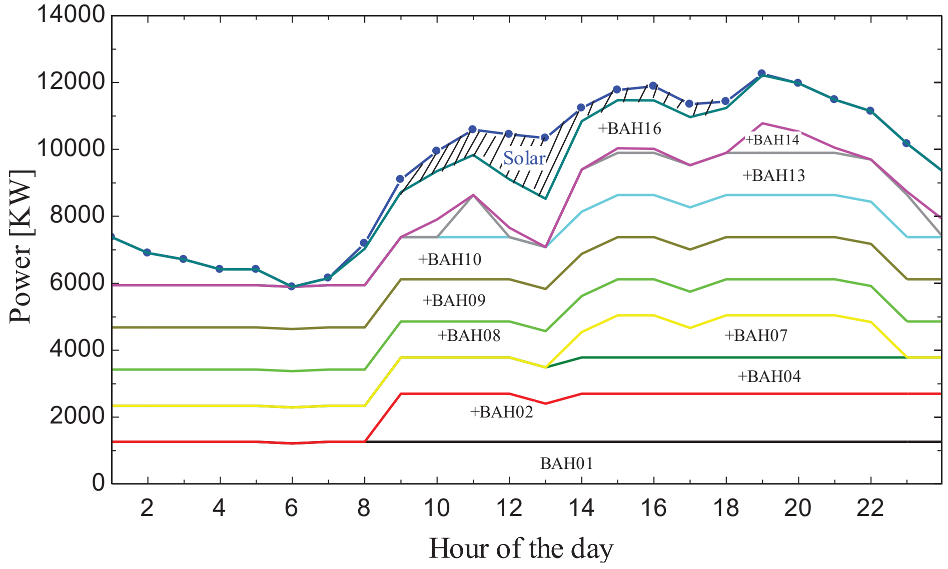

Figure. 10. One-day operational dispatch at the CHS with optimizing.

5.2. Sena Hybrid System

As observed in Figure 11, the Sena Hybrid System needed the operation of four generating units in addition to the solar energy contribution.

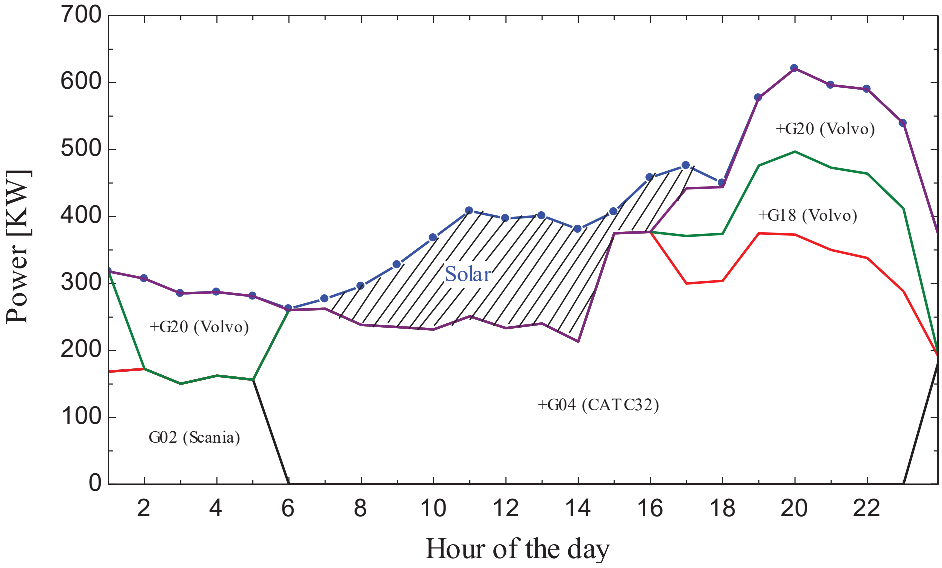

Figure. 11. One-day operational dispatch at the SHS without optimizing.

With the optimized model, the requirement reduces to 3 generating units, reducing at the same time the operative charge and use of personnel.

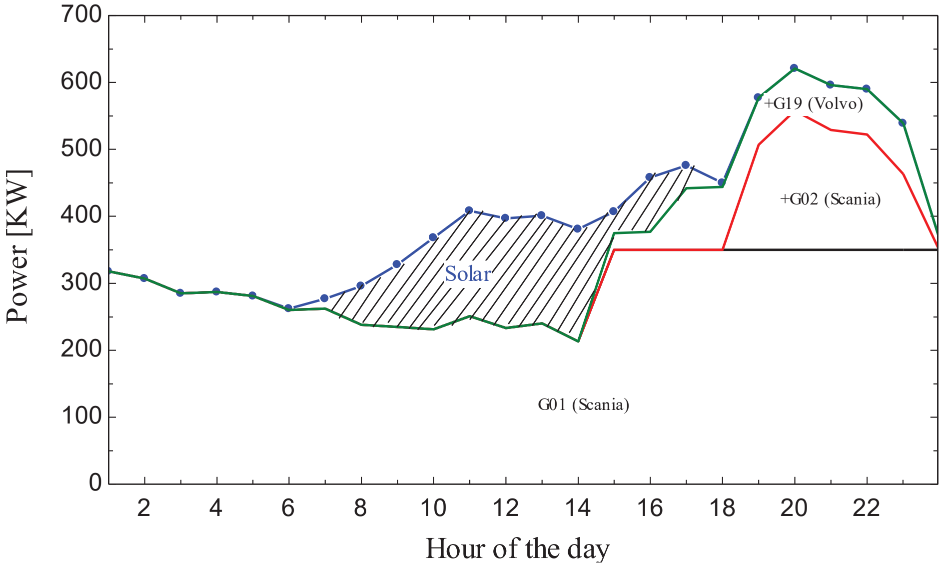

Figure. 12. One-day operational dispatch at the SHS with optimizing.

5.3. Gonzalo Moreno System

The Gonzalo Moreno System is a low-demand system, consequently, start-ups can create periods of time with no generation at all. As observed in Figure 13a, without the optimization the GMS required two units (G02 and G09) in one day, furthermore, the unit G02 was required on two occasions the same day. On the other hand, with the optimization model (see Figure 13b), the equipment should be connected 24 hours and produce a single start-up at least every three or four days, which is considered an appropriate period of time to make routine equipment inspections. Moreover, this slight change would allow us to save 73 L/day according to the optimization program.

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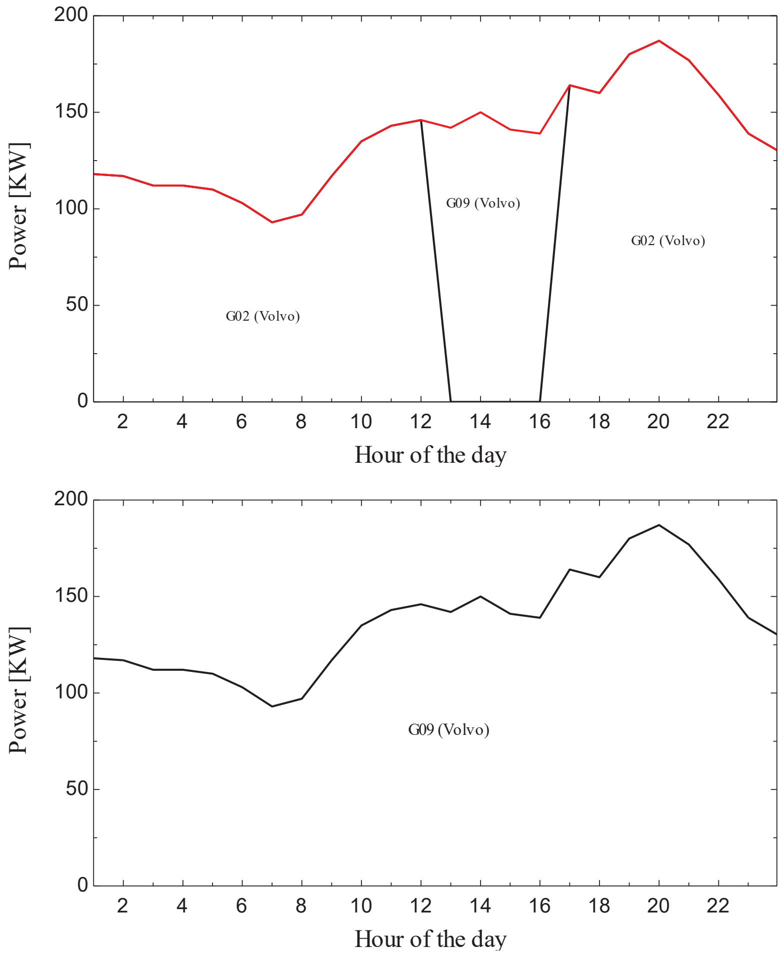

Figure. 13. *One-day operational dispatch at GMS, a) Without optimizing, b) With Optimizing*

7. Conclusions

The optimization tools for energy systems developed by Sempértegui-Tapia et al. [5] has been validated for three very different energy systems. The model works regarding the type (hybrid or purely thermal), the installed power (medium size cities or very small cities) or the demand characteristics (industrial, commercial or residential). The optimized energy systems provided an average daily savings in fuel consumption of 2211 L/day for the CHS, 182 L/day for the SHS and 73 L/day for the GMS. Which represent annual savings of 1.18 MM$ (CHS), 97 K$ (SHS) and 39 K$ (GMS). Thus, the savings obtained are between 5 and 9% of the annual cost of diesel fuel in Bolivia considering the international diesel fuel price (1.46 $/L).

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