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Hybrid Power Plants: A Case Study

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Abstract

Energy can be treated as an essential element for the development of society. Therefore, aspects like process' efficiency and environmental impacts must be considered when choosing the supply source. In Brazil, an event showed the fragility of a system that relies on in only one source to attend their necessities; a truckers strike made the whole country stop. The energy sector has a similar situation; more than 60% of Brazilian energetic matrix is represented by one source, hydroelectric power plants. The availability of solar radiation and wind in Brazil makes it possible to diversify its energetic matrix. Thus, the aim of this study is investigating the potential of hybrid solar-wind power plants in two basins of Minas Gerais—Brazil, São Francisco Basin and Jequitinhonha Basin, as well as compare their viabilities in order to address social issues. By analyzing INMET database and economic factors, the study has shown that it is feasible to implement renewable power plants in the basins of the study area, whether individually (solar or wind energy) or hybrid system. It shows in addition that hybrid system should be prioritized, since it presents lower cost, when compared to solar power plant, and more reliability due to seasonality of both sources.

Keywords: hybrid power plants, solar, wind, feasibility, São Francisco Basin, Jequitinhonha Basin

1. Introduction

Energy plays a very important role in society's development, thus it is present in almost every activity [1]. The author in [2] discussed one of the principal forms of energy, which is the electrical one and it can be obtained by a bunch of ways:

- a. Work transformations generated by mechanical energy from waterfalls and/or wind force.
- b. Thermal energy from the Sun which can be directly used as thermoelectric source or used on a photovoltaic way by means of panels.
- c. From heat (combustion, geothermal energy, sun, nuclear fission) through the use of thermal machines.

Some aspects are crucial when talking about energy. One is related to the environmental impacts associated to the energy production and that should always be the smallest possible [3]; another one is the exergy, “measures the ability of a source to produce useful work” [4], which will, in a second moment, be converted into electrical energy. Therefore, as some have been discussing, the production of energy must focus on efficiency [5].

In Brazil, the year of 2018 was tagged by an event that showed the fragility of a system that relies on only one source to attend their necessities. A truckers strike made the whole country stop [6]. The situation of energy supply is quite similar. **Figure 1** shows the Brazilian energetic matrix, where it is possible to see that more than 60% of Brazilian energetic matrix is represented by one source, hydroelectric power plants¹. Although hydroelectric energy can be considered a renewable source, it cannot be treated as a sustainable source² [7, 8]. When talking about sustainability, we are debating something that can endure over time, meeting the present generation needs without compromising the future generations’ needs [9]. It matters to find alternative resources to meet these requirements.

Renewable energy sources are playing an important role in the supply of energy for electricity, transport, heat, among others. It currently attends a range between 15 and 20% of world’s total energy demand. There is a bunch of alternatives of renewable energy resources, such as

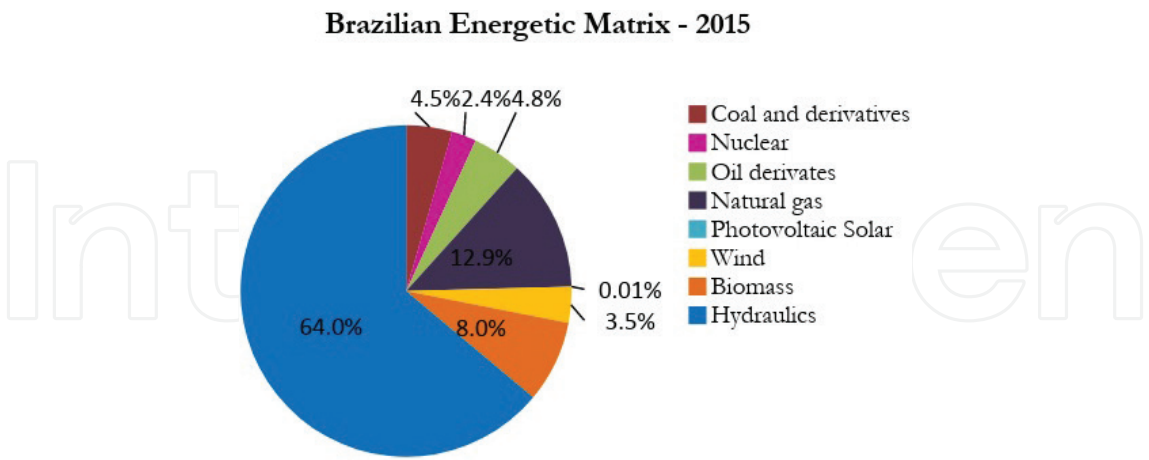


Figure 1. Brazilian Energetic Matrix—2015 [10].

¹In the world, about 20% of the energy supply is due to its source [8].
²The construction of a dam involves several social and environmental impacts, such as land flooding, people displacements, reduction on biodiversity, sedimentation, and so on [8].

biomass, geothermal, solar, modern bio-energy, wind, and it has been particularly favorable for more remote areas, such as rural areas [7, 8, 11].

Despite various options, two of them have excelled: solar and wind resources. The market of wind power and solar photovoltaic are being the most dynamic, with high rates of average growth [12, 13]. All around the world, for both, solar and wind sources, the availability of them is higher than the utilization's necessity [14, 15].

For photovoltaic generation capacity field, Brazil is compared with desert areas—which are the best places in terms of solar radiation—such as Dangola, city in Saudi Arabia desert [16] as well as in the wind field, Brazil has lack of capacity of production [15]. Despite of this quantity of “feedstock,” these systems are dependent of a series of natural variables, and a hybrid system that combines these two elements seems to be the ideal arrangement.

In Brazil, municipalities attended by the electricity service have a great representativeness, over than 95% of the total residences [17]. Nevertheless, speaking about rural areas, its coverage percentage is quite lower, reaching about 89.7%. The biggest energy lacuna is seen at the northern region, with something like 24% of rural households without electricity, followed by Northeast (7.4%) and Central West (6.8%) rural areas.

The municipalities of Jequitinhonha and São Francisco river basins have advanced positively in public services in the last few years. The energy sector has advanced considerably by increasing access to electricity from traditional sources to rural families in the region, reaching more than 90% of residencies.

Thus, this chapter has the objective of investigating the potential of hybrid solar-wind energy exploration in Minas Gerais, especially in the Jequitinhonha and São Francisco river basins, which is the most economically underprivileged region of the state, and with good natural characteristics, proposing a cost estimate based on the electricity consumption of each municipality.

1.1. Solar energy

1.1.1. *The solar resource*

The solar energy that hits the Earth's surface as sunlight is about 10,000 times superior as the humanity gross demand [18]. In this context, exist two basic “technologies that convert sunlight into useful forms of energy”. The first is the solar photovoltaic (PV) models/panels that directly convert sunlight into electricity. The second is a thermal system where the thermal energy coming from the Sun produces steam, and this last one is used to produce electricity. This thermal energy can still be used directly for water heat and/or industrial processes [8, 14].

1.1.1.1. *Photovoltaic energy*

The main uses of photovoltaic energy are observed for commercial purposes, residences, and public buildings; however, despite what one might think, these locations have great representativeness in energy consumption scenario. In Brazil, this value is 40% [19]. PV panels, which

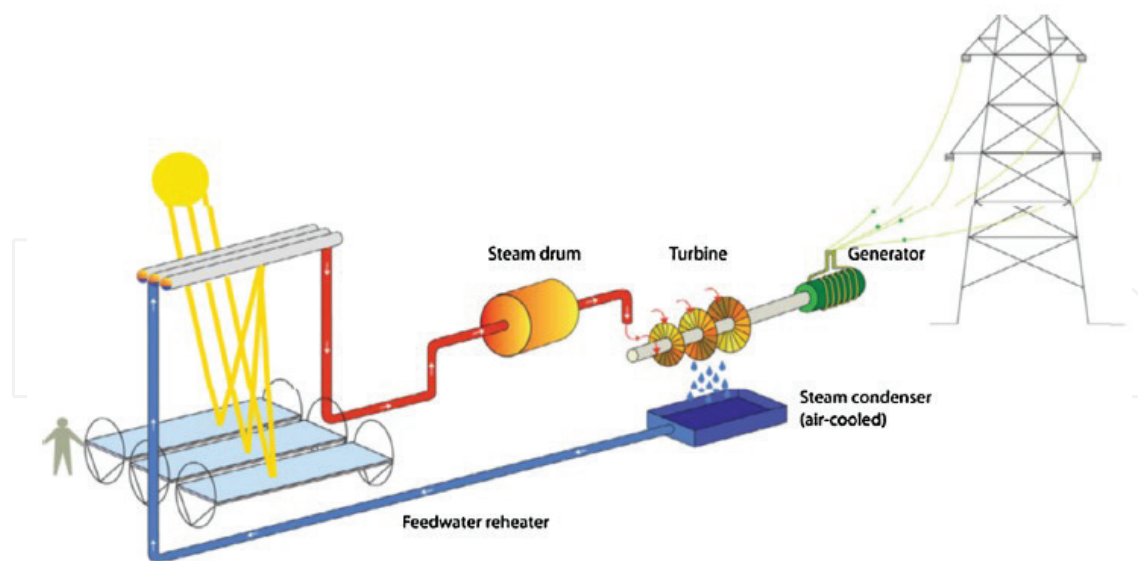


Figure 2. Solar thermal conversion system [24].

can be installed in series or parallel to generate direct current (DC), are used for this system, and they come in two different crystal structures: a polycrystalline and monocrystalline. The first one is usually less efficient because it is composed of just one crystal, making it cheaper; the last one has high efficiency, but it costs a bit more. Panels should not be chosen only based on its price, but many factors have to be put into account such as brand, physical size, durability, certifications. Moreover, the efficiency of PV panels depends on incoming solar radiation intensity, inclination of PV panels, wind speed, among others [19–22].

1.1.1.2. Thermoelectric use

The way of producing power, where thermal energy becomes electricity, happens in two processes, the creation of steam and the use of that steam to turn on a turbine, which generates electricity as we can see in **Figure 2**. Because of the turbines boundaries, this method has a low efficiency, about 25% [8, 23].

1.1.1.3. The Brazilian potential

Brazil has natural characteristics that favor the use of solar energy. It is located at latitude range with high incidence of solar radiation [14]. According to the solarimetric atlas [16], the northern region of Brazil has solar radiation compared with the best regions of the world, and its values of daily solar radiation, monthly average is 8–22 MJ/m², can be seen in **Figure 3**.

1.2. Wind energy

1.2.1. Windy resource

Seeking for technologies that minimize negatives impacts on the energy generation, the windy resource has gained attention. Beyond a production with no pollution during the power generation, it is widely available [8, 25]. “Wind energy is the kinetic energy contained

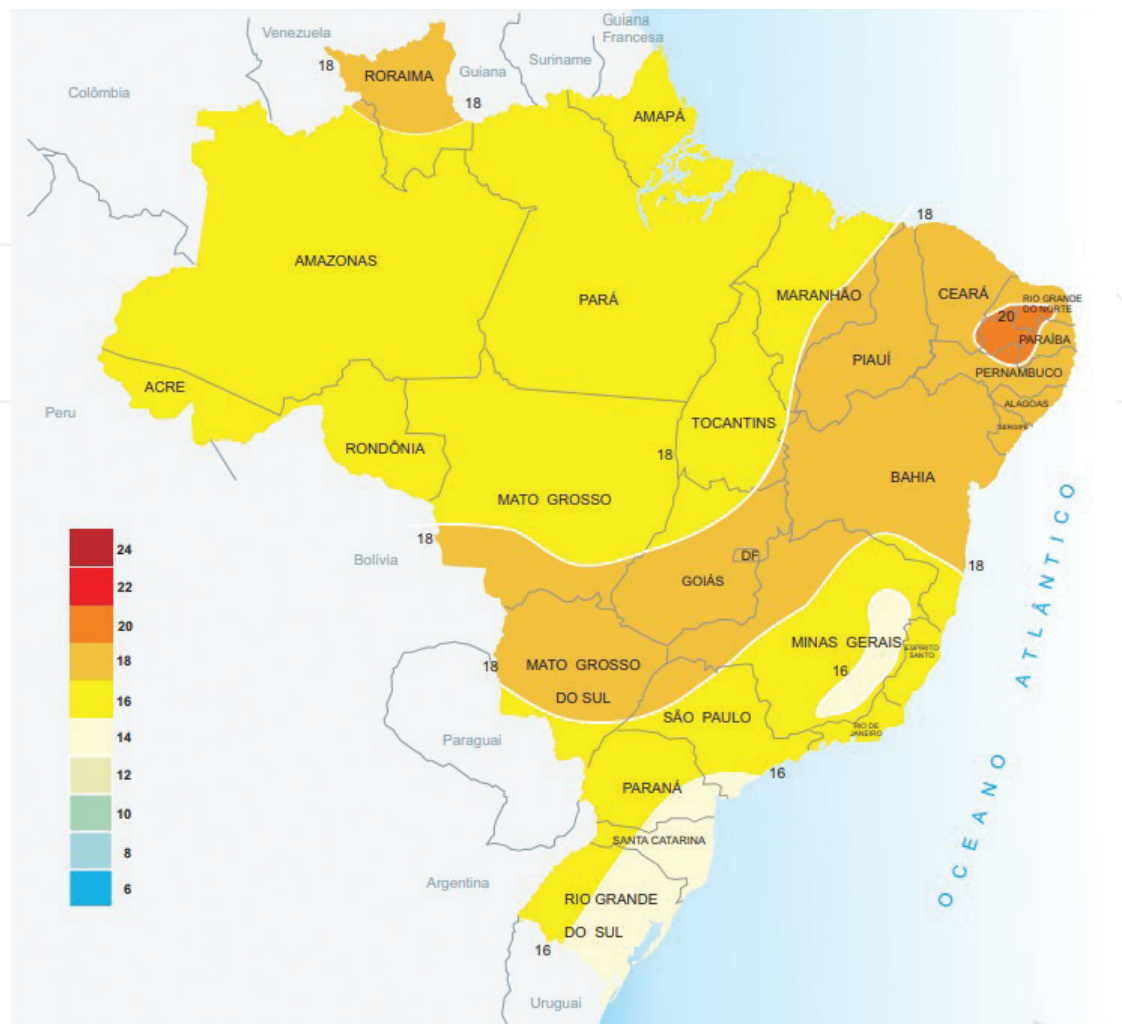


Figure 3. Daily solar radiation, monthly average-MJ/m² dia [21].

in the moving air masses.” Nevertheless, for this source to be considered technically feasible, its density must be higher or equal to 500 W/m², at a height of 50 m, requiring a minimum wind speed of 7–8 m/s [15, 24]. According to World Meteorological Organization, these special conditions are only found in 13% of the Earth’s surface [26].

1.2.2. Principles of technology

In order to obtain energy from the wind, some turbines are responsible to capture and transform the kinetic energy of the air mass into mechanical energy. Then, a generator is applied and converts the mechanical energy into electricity. A standardization has been established for turbines design as follows: horizontal rotation axis, three shovels, active alignment, induction generator and non-flexible structure [15, 24].

1.2.3. Brazilian and global scenario

The world’s capacity of energy production is about three times higher than the energy consumed all around the world in 2004; this value is 53,000 TWh/year, and the estimation of

consumption for 2020 is 27,326 TWh/year. Talking about Brazil, the majority of the studies speak of wind potential values of 60,000 MW [15].

1.2.4. Conflict points: economics and land use

Wind power generation system does not require any type of fuel for its operation, which represents an advantage. However, the equipment cost seems to be a problem. In addition, it requires special accommodating characteristics, such competing demand for land use.

For economics, the biggest issue is related to the investment cost (I_d), simulations ran by [27] has shown that investment cost is guide by the following equation:

$$I_d = C_s \cdot Ne \tag{1}$$

where C_s is the unity investment cost and Ne is the installed power. As wind generator represents the main part of C_s , its value is not as high as other types of energy. For land use, off-shore is an alternative [8].

1.3. Hybrid exploration

A hybrid renewable energy system (HRES) supply consists of two or more power generation technologies combined to enhance the system efficiency, and it can be considered a “modern environmental friendly solution.” The HERS can come either in stand-alone or in grid connected mode, showing itself as good option for remote locations [7, 28].

Renewable energy sources such as solar and wind are dependable of natural/climatic characteristics that are not easy predictable; therefore, the combinations of these two sources can increase the system effectiveness twice [29–31]. Another system that has gained attention is fuel-cell generation system, which demonstrates high efficiency and low pollution [32]. However, considering that these cells require pure hydrogen, and therefore, equipment to purify the fuel, it is not going to be used in this study, but its potential can be considered in future studies.

Figure 4 shows the scheme of a common solar-wind hybrid system.

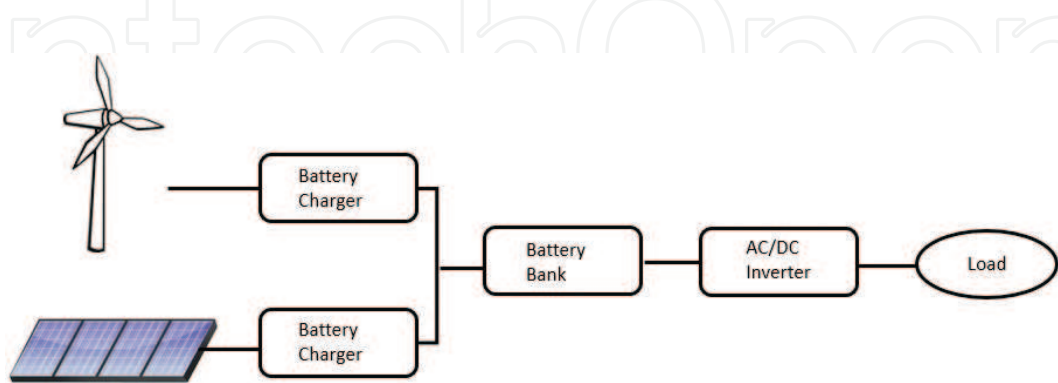


Figure 4. Diagram of a solar-wind hybrid system [11].

2. Methodology

2.1. Study area

Municipalities from two basins compose the study area: São Francisco and Jequitinhonha.

The São Francisco River Basin has great importance in the political, economic and social scenario of the country, considered the route of national integration through the connection between the Southeast, Midwest and Northeast regions of Brazil. The basins cover an area of 638,576 km², which corresponds to 8% of Brazil and 40% of the state of Minas Gerais. The São Francisco River born in Serra da Canastra in the state of Minas Gerais, covering 2863 km and contributing to the regional development of 521 municipalities in the states of Minas Gerais, Goiás, Bahia, Pernambuco, Sergipe, Alagoas and the Federal District [10, 31]. The vegetation in the region includes the transition area of Cerrado and the Caatinga with small fragments of Atlantic Forest with significant structure, complexity, and forest density. However, in the State of Minas Gerais, 96% of the Atlantic Forest and 75% of the Cerrado were deforested in their historical occupation process [17].

The São Francisco Basin presents distinct socioeconomic patterns that cover areas of high wealth and areas of high population density, as well as areas of intense poverty and well-dispersed populations, with rural population in the upper São Francisco with approximately 26% of the total basin [33, 34]. The basin has multiple uses, 77% of total demand for irrigation and 12% for hydroelectric power supply [35].

The Jequitinhonha River Basin has an area of approximately 70,315 km², and 65,660 km² (93%) is located in the state of Minas Gerais. The basin is bordered in the west by the São Francisco river basin. The Jequitinhonha river has its source in the Serra do Espinhaço, covering 920 km [36]. The basin is characterized by significant climatic heterogeneity, acting in a dynamic way with the physical and biotic means that are determinant for significant geoenvironmental features, including ecological and cultural patterns that influence the modalities of the use of natural resources [9]. The vegetation is composed of cerrado, fields and transitional vegetation of the Atlantic Forest and Caatinga [33].

The region has a high poverty rate with high exodus to large centers and more than two-thirds of the population occupying the rural area. The main human activities are related to agriculture, mining and garimpo [37].

Municipalities were chosen from these two basins based on the social perspective as well as renewable resources availability, and also considering if the city had National Meteorological Institute (INMET) station, so that it would be possible to analyze the real date. From São Francisco Basin, the cities were: Curvelo, Espinosa, Montes Claros, Ouro Branco, Pirapora, Pirapora, and Três Marias. From Jequitinhonha Basin: Águas Vermelhas, Almenara, Belmonte, Capelinha, Diamantina, Itaobim, Rio Pardo de Minas, and Salinas (Figure 5).

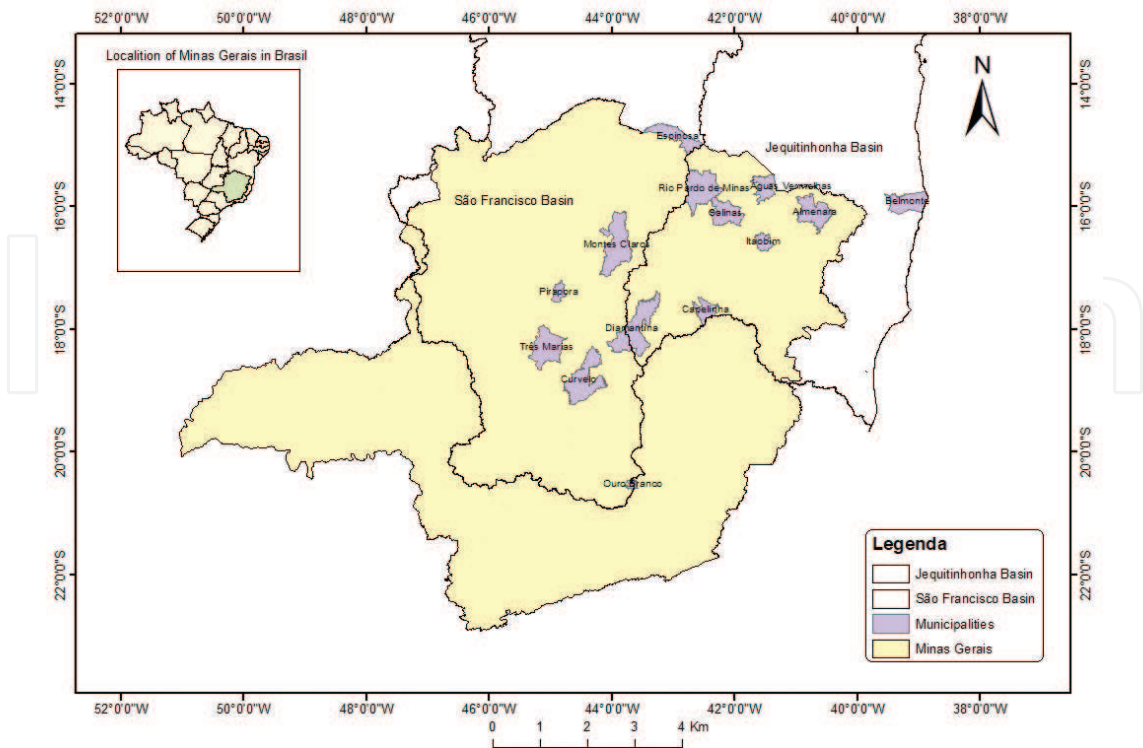


Figure 5. Representation map of municipalities location [11].

2.2. Energy consumption

Understanding energy consumption and need of each municipality is crucial to a successful work and that reveals the reality; therefore, based on the approach used by [38], average residential energy use [10] and residential coverage [17] data were collected.

2.3. Hybrid potential

For the hybrid potential, bibliographic research and INMET (National Meteorological Institute) database were used in order to understand the natural resources available (solar radiation and wind) and how those renewable energy works [39].

Renewable energy resources, solar and wind, were studied through bibliographic research, as well as, their availability on the municipalities what compose the study area. The main bibliographies used were solar and wind atlases of Minas Gerais and Brazil [40–43]; but also, the study counted on interview with expert in the field of energy [44, 45]. The cities were chosen focusing on the social aspect and solar/wind availability.

INMET database, which contains radiation and wind velocity records for fourteen municipalities that compose the study area (Águas Vermelhas, Almenara, Belmonte, Capelinha, Curvelo, Diamantina, Espinosa, Itaobim, Montes Claros, Ouro Branco, Pirapora, Salinas, Rio Pardo de Minas, and Três Marias), provided real date necessary to validate this work. From these data, the means of radiation and velocity of the winds were taken for each of the municipalities for

all months of the year, considering a period of 3 years of data for each municipality. Since the data from INMET database were provided in different metric system of those used in energy system, adjustments, conversions and weight were made on it.

Kruskal-Wallis nonparametric variance test and for Dunn's test, the Dunn's test was used in order to comparatively analyze solar radiation and wind velocity data for the municipalities. Dunn's test was used in the BioEstat 5.3 program [46].

2.4. System dimensioning

The dimension and design of a hybrid system are ruled by three factors: energy consumption, efficiency of the equipment, and availability of natural resources. For this project, was defined that the use of each of the renewable resources would follow the criteria of lower price, while meeting the energy demand [47].

Following [38] approach, generic models of photovoltaic and wind power systems were used according to [48] for a close-to-reality system design. The specification is shown in **Table 1**. It is worth mentioning that the amount of equipment required to each location differs, since their energy use, need, and natural resources are different.

Eq. (2) [37] represents the electricity generated by a photovoltaic system. It evaluates the area of the panel in m^2 (A); the efficiency of the panel in percentage (r); average solar radiation (H) and; a performance ratio, which represents the loss coefficient and ranges 0.5 and 0.9 (PR), the standard value of PR is 0.75. The evaluation gets an energy value (E) in kWh.

$$E = A * r * H * PR \quad (2)$$

It is worth mentioning that the photovoltaic-software calculator was used in order to calculate the photovoltaic electric generation. The calculator uses Eq. (2).

For wind power, the equation evaluates density of air, which is given in kg/m^3 (ρ); area of the wind turbine, considering the diameter of the rotors (A); the wind speed (V); aerodynamic coefficient of rotor power (C_p) and; the efficiency of generator and transmission set (η), Eq. (3).

$$P(\text{Watts}) = 12 \rho A r V^3 C_p \eta \quad (3)$$

Equipment	Nominal power/capacity	Cost (RS)	Lifespan (years)
PV module	1 kW	1500	25
Wind generator	10 kW	1000	20
Battery bank	1 kWh	70	10
Inverter	2000 Wp	800	20

Table 1. Equipment specification [47].

When comes to wind sources, it presents different speeds in its vertical profile. Normally, wind turbines are located 30 m above the ground, but wind speed is measured at 30 m from the ground in INMET stations; therefore, Logarithmic Law of the Winds has to be used in order to obtain reliable data of wind speed [49]. The law follows Eq. (4); where velocity (V) of a wanted point (Z) is a function of a velocity (V_{ref}) at a known point (Z_{ref}) and Roughness length in the current wind direction (Z_0). As all the cities of the study area are located in Minas Gerais, Z_0 is assumed 1 m, based on the Atlas of Brazilian wind potential [8].

$$V = V_{ref} \frac{\ln(Z/Z_0)}{\ln(Z_{ref}/Z_0)} \tag{4}$$

3. Results and discussions

3.1. Energy consumption

In 2014, the energy consumption in Minas Gerais was 10,698 GWh and the number of residences covered by this power was 6,884,946 [17]; thus, the average residential consumption of the state was 1.55 MWh/year or 129 kWh/month. The residential electrical consumption of the studied municipalities is shown in **Table 2**.

Montes Claros, since it is the most populous municipality of the study, is also the one that presents greater consumption of the residential class.

Municipality	Nº residencies	Municipality consumption (GWh/year)
Águas Vermelhas	1781	0.23
Almenara	10,168	1.31
Belmonte	723	0.09
Capelinha	52,549	6.79
Curvelo	45,574	5.89
Diamantina	9322	1.20
Espinosa	7109	0.92
Itaobim	6024	9.90
Montes Claros	99,667	0.78
Ouro Branco	10,355	12.87
Pirapora	15,006	1.34
Rio Pardo de Minas	6006	1.94
Salinas	10,156	0.78
Três Marias	8176	1.31

Table 2. Energy consumption of the studied municipality [10, 31, 37].

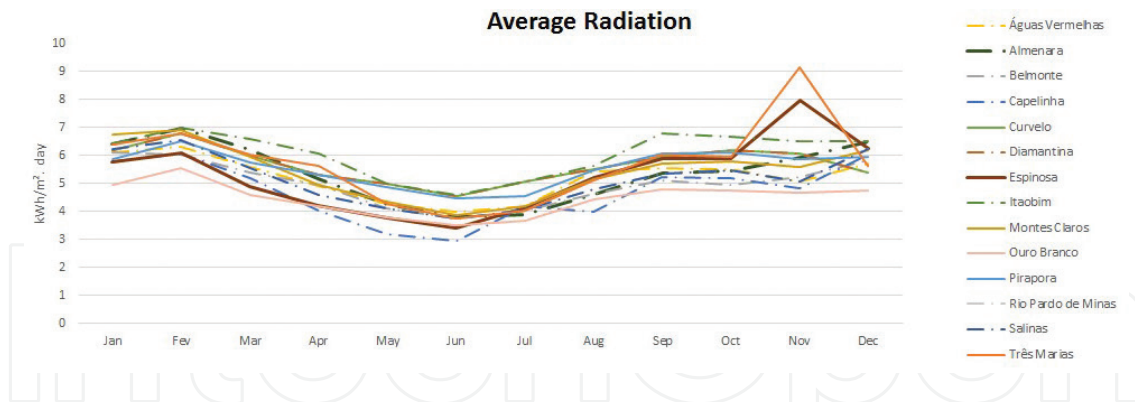


Figure 6. Average radiation for studied municipalities [11].

3.2. Hybrid potential

The hybrid potential is measured by the availability of renewable source, radiation index and wind speed. For photovoltaic purpose, a municipality is considered apt when the average radiation index is $5.5 \text{ kWh/m}^2 \text{ day}$ [25]. The municipalities that compose the study area show the following radiation ($\text{kWh/m}^2 \text{ day}$ [50]), according to analyses of INMET database, Águas Vermelhas 5.6; Almenara 5.5; Belmonte 5.0; Capelinha 4.7; Curvelo 5.7; Diamantina 5.3; Espinosa 6.2; Itaobim 5.6; Montes Claros 5.7; Ouro Branco 4.5; Pirapora 5.9; Rio Pardo de Minas 5.2; Salinas 5.9 e; Três Marias 5.7 (Figure 6). Regarding the basin, for Jequitinhonha Basin, Belmonte and Capelinha are not able to receive a photovoltaic system, and for São Francisco Basin, Ouro Branco is not able to support this sort of system in the parameters of this study. Another important factor for this study is daytime radiation (insolation), which is shown in (Figure 7), the pattern is that radiation increases during the day until reaches the highest values at 15 h (3 p.m.), showing slitting smaller values at 16 h (4 p.m.), when they start to decrease again. The decrease factor revealed to be faster than the increase. For wind energy, the turbines are activated when the winds reach a speed of 3 m/s. For the study area, the municipalities that have shown feasibility for the implementation of wind energy system are Diamantina, Espinosa, Ouro Branco, Rio Pardo de Minas, and Três Marias (Figure 8). The municipalities that have both solar and wind potential are Espinosa and Três Marias

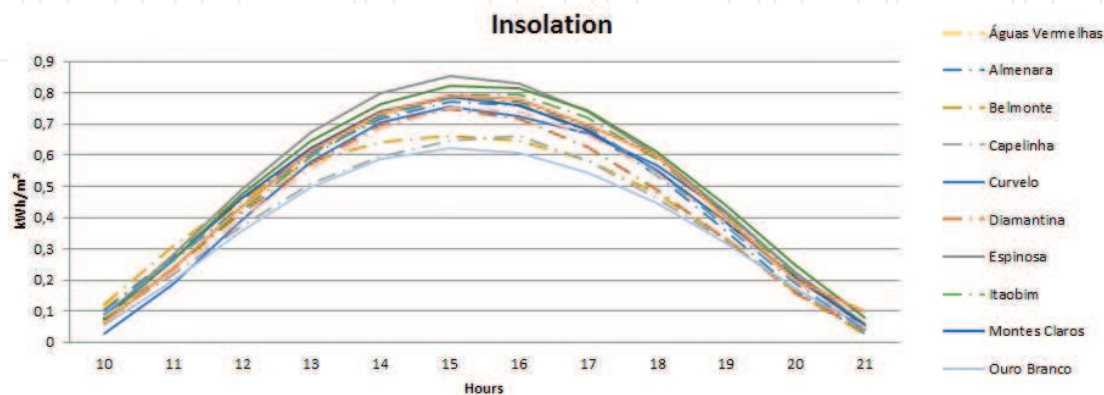


Figure 7. Average insolation for studied municipalities [11].

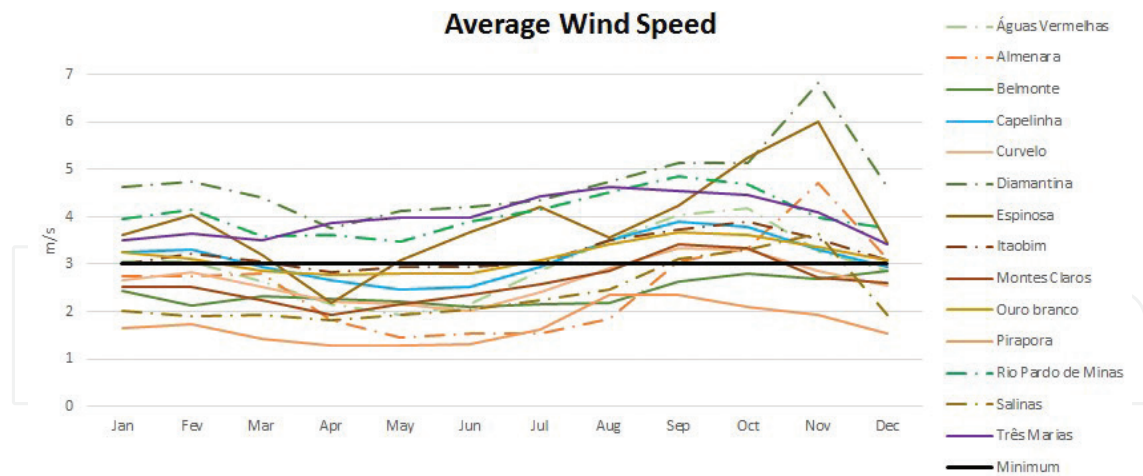


Figure 8. Average wind speed for studied municipalities [11].

(both of them from São Francisco Basin); therefore, they are able to receive a hybrid system. These data were corroborated by the variance test that indicated a significant difference of these municipalities in relation to the others that were analyzed ($H = 72.0573$; $p < 0.0001$). It is worth mentioning that the Logarithmic Law of the Winds were applied to every municipality considering 30 m from the ground, which means that some of the cities would be able to receive this system at higher altitudes; however, it would be so much expansive that would be economically unfeasible.

Of the municipalities eligible for the hybrid system, only Espinosa has no wind availability during 24 h of the day (Figure 9).

3.3. System dimensioning

Dimensioning a system depends on the demand and resource available. For this study, dimensioning follows the principle of supplying 100% of cities demand for residential category.

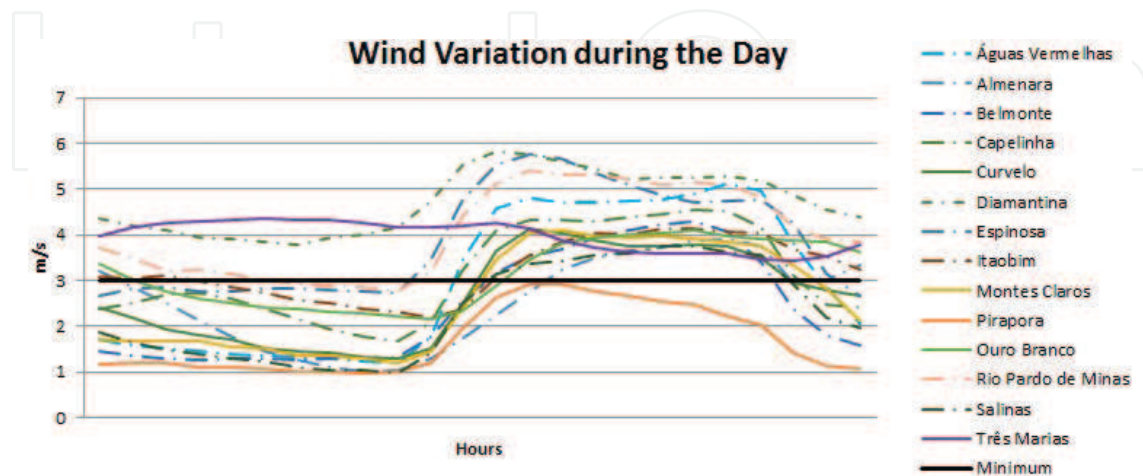


Figure 9. Average wind behavior during the day for studied municipalities [11].

The representation of each part of the hybrid system will be done by “f” as the photovoltaic portion and (f-1) the wind part. For municipalities where wind average was not enough to carry a wind system, (f-1) is equal to zero; therefore, the entire demand will be supplied by f (photovoltaic system). The size of “f” also differs among cities, for the difference of demand as well as solar radiation and wind speeds [38].

Analyses from INMET databases have shown that some municipalities have potential for solar system (Águas Vermelhas 5.6; Almenara 5.5; Curvelo 5.7; Itaobim 5.6; Montes Claros 5.7; Pirapora 5.9; and Salinas 5.9), other for wind system (Diamantina, Ouro Branco, and Rio Pardo de Minas), and two of them for hybrid system (Espinosa and Três Marias). Just Belmonte and Capelinha revealed to be incapable to comport any of the system in the parameters of this study.

For the hybrid-system-municipalities (Espinosa and Três Marias), (f-1) is different from zero. For Diamantina, Ouro Branco, and Rio Pardo de Minas, “f” is equal to zero and for all other (f-1) is equal to zero, except for Belmonte and Capelinha, which did not meet the minimum standards considered in this study.

A simulation of prices, amount of equipment for each municipality is shown in **Table 3** following the specifications and prices (considering batteries and inverters as well) mentioned in Section 2.2.3 (**Table 1**).

The simulations shown in **Table 3** reveals that, when technically feasible, hybrid systems should be prioritized, since they show lower cost and are more reliable considering seasonality of solar

Municipality	Consumption (GWh/year)	N° Panels	N° of wind generators	Estimated cost (R\$)
Águas Vermelhas	0.23	1.09	0	1,195,646.15
Almenara	1.31	6	0	6,581,538.46
Belmonte	0.09	—	—	—
Capelinha	6.79	—	—	—
Curvelo	5.89	25.69	0	28,179,953.85
Diamantina	1.2	0	100	423,000.00
Espinosa	0.92	25	90	408,123.08
Itaobim	9.9	44.89	0	49,240,876.92
Montes Claros	12.87	55	0	60,330,769.23
Ouro Branco	12.88	0	1000	4,230,000
Pirapora	1.34	5727	0	6,282,078.46
Rio Pardo de Minas	1.94	0	190	803,700.00
Salinas	0.78	3365	0	3,691,146.15
Três Marias	1.06	40	105	488,026.92

Table 3. Energy consumption of the studied municipalities [11].

and wind resource. The wind resource is the second resource that presents the best initial cost, losing only to hydroelectric power stations [51], which proves the data obtained in this study.

3.4. Environmental and social perspective

Although solar and wind energy represent a sustainable and renewable source of energy, they still have negative impact that have to be considered and mitigated, even if their impacts are small compared to traditional sources [52].

With regard to the environment, the raw material for solar energy is silicon, which has to be mined; therefore, all the mining impact has to be considered and represent the main impact of photovoltaic panels. Even though this is a negative impact, it also represents an advantage for Brazilian market, since the country has large reserves of quality quartz that can generate silicon with high purity, cells and solar modules [53].

For wind energy, the main impact is the death of birds due to collision. It is estimated that collisions with wind turbines kills approximately 20,000 to 37,000 birds per year [54]; however, this number represents only 0.003% of birds death, since other anthropological activities have a major influence on this number, such as building, car, chemicals. For wind energy, there are still noise and visual pollution.

Other impact to be quoted is the land use for both systems, since they require a large area [55].

For social, there is much gain in this sort of energy system. First, these systems do not release pollutant, so they are safer and healthier, the greenhouse gas life cycle for renewable energy, including manufacturing, installation, operation and maintenance and dismantling, is minimal [56]. Substituting fossil fuels for renewable energy can reduce premature mortality and generally reduce health costs [57].

Another benefit is that solar and wind systems do not represent conflict of use of water, since they require little use of water [58]. In addition, they require more labor, so they create more jobs per invested currency, and jobs tend to be created in rural areas, which help to avoid rural exodus [58, 59].

4. Conclusions

In Brazil, the year of 2018 was tagged by an event that showed the weakness of a system that relies on in only one source to attend their necessities; a truckers strike made the whole country stop. The energy sector has a similar situation; more than 60% of its energetic matrix is represented by one source, hydroelectric power plants. So, due to the importance of the energy sector, the energetic matrix needs to be a bit diversified.

The analyses carried on in this study demonstrated that Minas Gerais, more specifically municipalities on São Francisco and Jequitinhonha Basins, shows technical feasibility to receive renewable energy system, whether solar, wind or hybrid system. The economical

analyses also revealed that it is economically viable, nuclear power plants, Angra I and II nuclear plants, with a combined capacity of about 2000 MW, received an investment of R\$ 6.576 billion [58], a photovoltaic field of this proportion (2000 MW) would cost about R\$8 billion, as shown in this project (see **Table 3**, Pirapora), this option has a close price of what was spent in the nuclear power plants, and it is a cleaner option, free of risk to the population.

Even though hydroelectric plants continue to be more economically viable [44, 45], the use of other source of energy is important in order to protect Brazilian market, diversifying national energy matrix.

After all, the study has shown that hybrid system is a viable alternative for Minas Gerais, specially the basins of São Francisco and Jequitinhonha. In addition, it could represent the crucial change to address social issues in these basins.

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