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Study of economic viability and energy availability of hybrid solar / wind power and cooling systems with thermal energy storage

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ABSTRACT

A large portion of the energy consumed worldwide is used for heating and cooling environments. In Brazil, the use of solar energy in homes experiences an increasing, despite the fact that not always an exclusively solar system can meet the entire energy demand, since climatic conditions significantly influence energy generation and its energy efficiency. Therefore, it is recommended to have alternatives to guarantee energy needs at consumption points throughout the year. In this context, with the intention of deepening the issues involving the complexity contained in the understanding and quantification concerning energy and budget of projects of refrigeration systems built – or to be built – based on the use of hybrid energy, the present work aims the dimensioning of an online simulator to assist the development of projects for installations of photovoltaic and wind systems in homes, businesses and industries. In addition, the study aims to deliver differentiated and personalized projects, combining good efficiency and lower operating costs. This simulator (website / application) uses API (Application Programming Interface), integrating Python programmed scripts to the platform branches, in order to offer, in a single Web platform, the complete simulation of the project of solar panels and wind turbines, budget, indications suppliers, service providers and estimated power output. Input data are: geographical position (altitude and longitude), available area (m2), roof material (ceramic, polycarbonate, glass, etc.), building height (m), historical data on solar and wind incidence (collected from INMET and INPE sites, respectively) and monthly average of the last years of power consumed (kWh). Output data are: estimation of the power produced by the system and economic analysis, number of panels and wind turbines needed to produce the necessary power, focusing on storage via TES (Thermal Energy Storage), as well as the impact of the study on economic and energy analysis of the system.

KEYWORDS: Refrigeration Systems; Hybrid-Solar / Wind Energy; API; Thermal Energy Storage.

1 INTRODUCTION

The awareness about climate change influenced by us is no longer new, science explains that changes in the global climate are a fact and happen mainly due to the influence of human activity. The verification of the lack of information on distributed electricity generation encouraged the development of this information system/application. The main objective is to disseminate the benefits of decentralized generation and the consecutive financial and environmental savings related to this practice. Currently, any individual or legal entity can be part of the energy compensation system for agents that generate more than they consume (ANEEL, 2014).

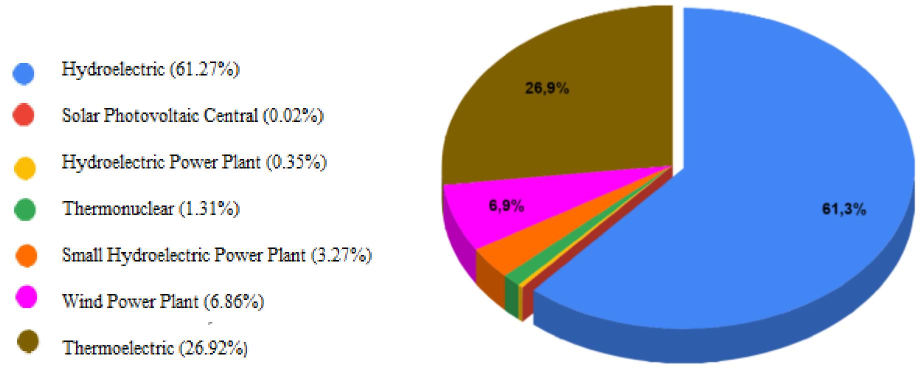
The studies of the Intergovernmental Panel on Climate Change (IPCC, 2018), indicate that, if all greenhouse gas emissions ceased today, those already present in the atmosphere would be responsible for warming the planet by at least 1º C by 2100. Thus, the objective of this work is to raise awareness and disseminate the application of renewable energy sources to reduce greenhouse gas emissions. In addition to the ease in budget estimation and calculation of energy availability, through a unique and free simulator portal that will act as a facilitator for future projects and parameterization for projects already executed.

The temperature in urban areas is higher, when compared to rural areas, for several reasons, such as the absorption of heat by concrete, asphalts, concentration of people, vehicles, machines, etc. The temperature difference between rural and urban areas is 5º to 9º C according to the United Nations Environment Program.

This temperature difference led to a greater need for the use of refrigeration equipment, these have a considerable energy consumption. This cooling transfers excess heat and emits greenhouse gases, which in turn heat the planet even more and consequently more and more cooling is needed. Generating an irreversible cycle of great impact on climate change. "Around 40% of the energy consumed by buildings worldwide is used for space heating and cooling," according to Martina Otto, who heads the secretariat of the Global Alliance on Buildings and Construction at the United Nations Environment Program (UNEP). "Room cooling is among the fastest growing energy uses in buildings. With higher temperatures, more urbanities and ever higher living standards, we will need a multitude of solutions to provide thermal comfort while protecting human health." According to the IEA (International Energy Agency), the energy consumed by these devices is expected to triple by 2050, which means that devices around the world will be using all the current electrical capacity of the United States, Europe and Japan, combined. Rising heat waves severely damage the health of the population, contribute to heat-related deaths, reduce labor productivity, worsen air quality, and disproportionately affect poorer communities. It is therefore of the utmost urgency that we make these systems as effective as possible, and that cities learn alternative ways of cooling.

The increased demand for refrigeration systems would not matter as much to the environment if all the electricity they consume came from renewable sources. The classic means of energy production (Fossil and hydroelectric), are polluting ways and are being increasingly questioned, in this sense, ways to generate renewable energy are more present in the energy scenario, however, the total number of homes and establishments that use this The alternative is not yet significant, due to the high cost and mainly due to the lack of information on the topic, as shown in Figure 1, Adapted from ANEEL's Generation information bank.

Figure 1. Brazilian electrical matrix in May 2017.



Studies in the area are betting on the popularization of the use of renewable energy, as long as the different methods are applied together, they are called hybrid energy systems. It usually consists of two or more energy sources used together to provide greater yield/performance to the system, for example, a photovoltaic panel installed together with a wind turbine configures a hybrid energy. This combination is called energetic complementarity. In homes, it is expected that wind energy will be more efficient in winter, while during the summer solar panels will have their peak energy production. Hybrid energy systems bring greater environmental benefits than independent systems for generating solar, wind, biomass, hydrous etc.

There are downsides in the use of renewable energy, but this only happens if we only depend on one type of energy, for example, if every form of energy were to be wind turbines, the air currents would undergo changes that would affect the planet's climate , similarly, if we used only solar energy, the level of heat from the sun that reaches the earth would decrease and the planet would be colder. However, if we find ways to complement them, we could live harmoniously with the resources made available by the environment for a long time.

2 ENERGY POTENTIAL

In Brazil, CPTEC/INPE operates and manages a wind and environmental data collection network aimed at meeting the demand for information in the energy sector - Rede SONDA. The main objective of the SONDA network is to provide information that allows the improvement and validation of numerical models for estimating the energy potential of renewable sources.

Another important result of work developed by Brazilian researchers is the Atlas of Brazilian Wind Potential [1]. The wind information contained in this database was generated from the simulation of large-scale atmospheric circulation by a mesoscale model called MASS (Mesoscale Atmospheric Simulation System). From these geostrophic wind data, physical refinement with the WindMap code was used to estimate wind data at the typical height of wind turbines (50 m). According to the Atlas of Brazilian Wind Potential, more than 71,000 km2 of the national territory has wind speeds above 7 m/s at the level of 50 m, which provides a wind potential of around 272 TWh/year of electricity. This is a very significant figure considering that the national consumption of electricity is 424 TWh/year. Most of this potential is off the coast of the northeastern states, as a result of the trade winds.

The survey of wind energy resources in Brazil was one of the goals of the SWERA project (Solar and Wind Energy Resources Assessment) developed under the coordination of the Climate and Environment Division of the Center for Weather Forecasting and Climate Studies (DMA/CPTEC) and funding from the United Nations Environment Program (UNEP). The methodology used in the mapping of wind resources adopted the Eta numerical model, routinely used for weather forecasting and climate studies by CPTEC/INPE.

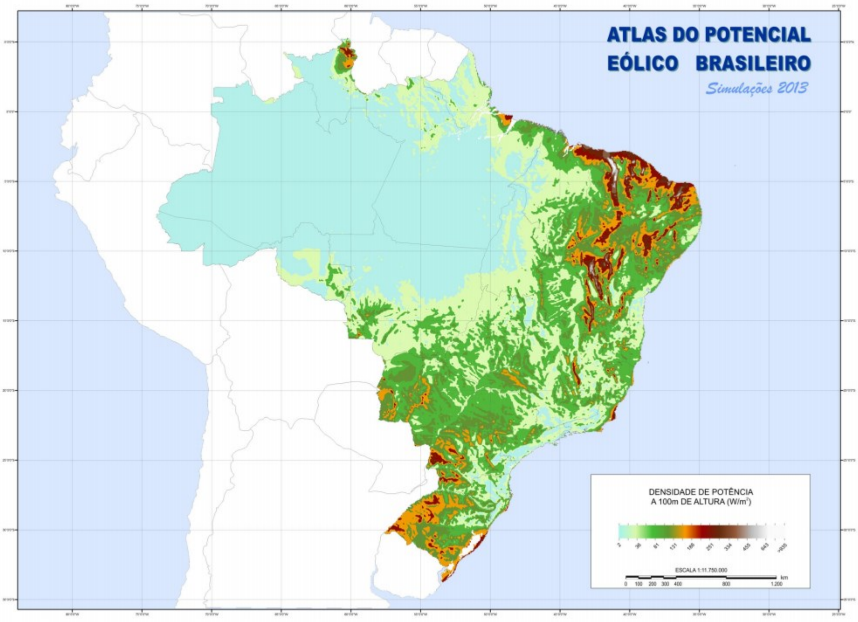
The mapping produced with the Eta model is in good agreement with the results presented in the Brazilian Wind Atlas, with the largest discrepancies being observed in the south of the state of Bahia and on the border between Bahia and Piauí. However, due to the scarcity of field data in the regions with the greatest discrepancy between the two methodologies, it is still not possible to say which one is more reliable. More detailed information on the mapping of wind resources in Brazil carried out during the SWERA project can be accessed on the portal http://swera.unep.net/swera/ and on the SONDA network website (www.cptec.inpe.br/sonda).

2.1 Brazilian Wind Potential

The Atlas of Brazilian Wind Potential, see figure 2, published in 2001 and designed for a height of 50 meters (enough height for the technologies of wind turbines at the time), was, without a doubt, an important milestone for the development of the wind sector in Brazil. Over the years, the Brazilian wind market has experienced significant growth, both due to the implementation of the Incentive Program for Alternative Sources of Electric Energy - Proinfa, as well as the results achieved by the energy auctions. Over time, wind turbine technology has developed significantly, providing models with greater power and dimensions for operation at higher heights, when compared to models sold in 2001.

INPE's web ambience for querying data was developed in order to provide users with the possibility not only of viewing information from each thematic map, but also of making comparisons between two different themes, in addition to other map features available in a georeferenced environment. With a single click, it is possible to obtain all the information contained in the thematic maps, both for a specific point and for a previously defined region. The Atlas provides the entire consolidated and georeferenced database in a web environment for free consultation.

Figure 2. Map of the Brazilian wind potential.

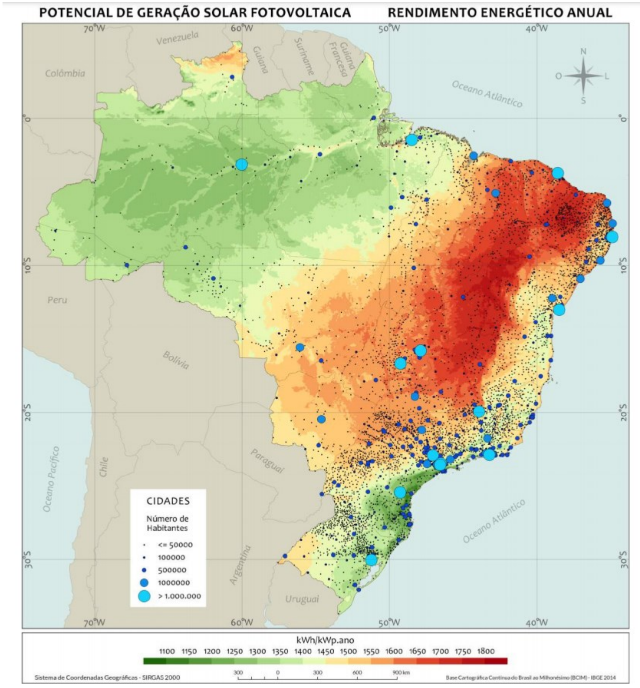


2.2 Brazilian Photovoltaic Potential

Photovoltaic electricity generation has great potential in Brazil, as shown in the map in Figure 3, from Brazilian Solarimetric Atlas. In the less sunny place in Brazil, it is possible to generate more solar electricity than in the sunniest place in Germany, for example. The map shows the maximum annual energy yield (measured in kWh of electricity generated per year for each kWp of installed photovoltaic power) throughout the national territory, both for large centralized and ground-installed plants, as well as for distributed photovoltaic generation integrated in roofs and roofs of buildings. The average annual performance rate of 80% was adopted to simplify the analysis and represents the performance of a well-designed and installed solar photovoltaic generator with good quality equipment and labeled by INMETRO.

Population concentration is also shown through the blue circles spread across the Brazilian territory in this figure. It is important to note that in the summer months, mainly from December to March, generation is maximum in the southern and southeastern states of Brazil and coincides with the maximum demand registered by the National System Operator – ONS for these regions. In this context and due to its distributed nature, solar photovoltaic generation also has a great potential to contribute to the reduction of demand peaks in the transmission systems of the National Interconnected System – SIN. In the coming years, with the increasing penetration of solar photovoltaic generation throughout Brazil, electricity generation close to the point of consumption should be recognized by the electrical system as one of the main attributes of this generation technology. With the sharp reduction in costs experienced by photovoltaic technology in recent years, the scenario is becoming increasingly favorable to its adoption on an increasing scale.

Figure 3. Map of the Brazilian Solar Potential.



3 SIZING OF THE HYBRID ALOM SYSTEM

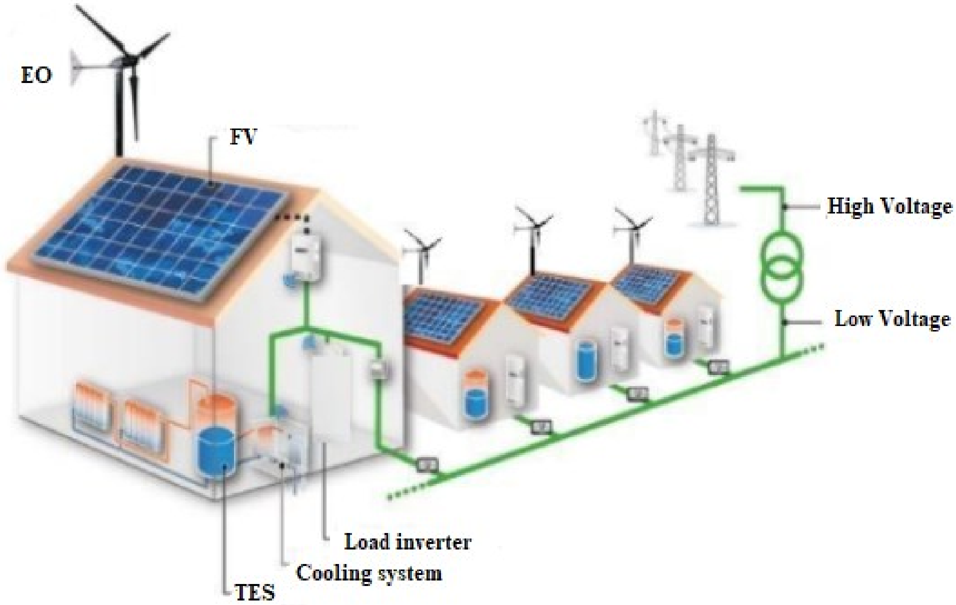
This topic aims to present the methodologies adopted in this work for the study of the technical and financial feasibility of a hybrid system, Wind (WS)-Photovoltaic (PV), for refrigeration systems using thermal energy storage (TES) and evaluating the configuration that will generate the lowest cost-benefit, as identified in figure 4, adapted from the website of the Center for Solar Energy and Research o Baden-Württemberg-ZSW.

Blasques et al. (2014) describe that correct hybrid system(HS) sizing is complex, due to the presence of more than one source (intermittent or constant), the storage system and the cost. The authors propose an algorithm for HS sizing of electric power generation, in order to present the lowest cost configuration and also a proposal for the operation and management of the system. The optimized sizing of a HS is an extremely important step to get low investment costs and control of the plant throughout its life.

The system created in the scope of this study, called Hibrid Álom, structured an API to work with data from different sources, it is a tool that performs communication between applications to share their actions, tools, standards and protocols. This interface generates software-to-software conversation, it is a process carried out in the back-end of applications, where the user does not see the request and response interaction happening. What he notices is the possibility of carrying out different tasks in one place. That is, multiple tasks from different platforms are completed in one place. Figure 5, Adapted from Google Dialogflow Documentation, shows the interactions used in the back-end of the Hibrid Álom application.

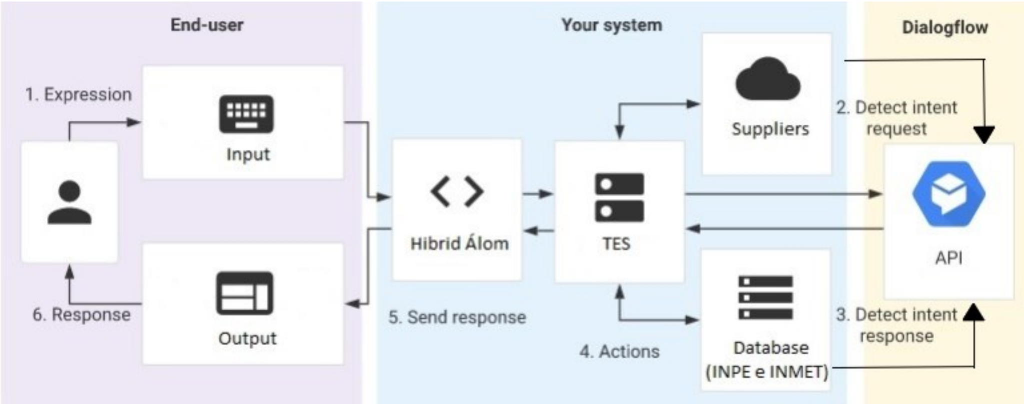
R. bras. Planej. Desenv., Curitiba, v. 10, n. 04, p. 719-734, Edição Especial Reflexões do Planejamento e Governança na preservação do meio ambiente, dez. 2021.

Figure 4. Schematic model proposed by the author.



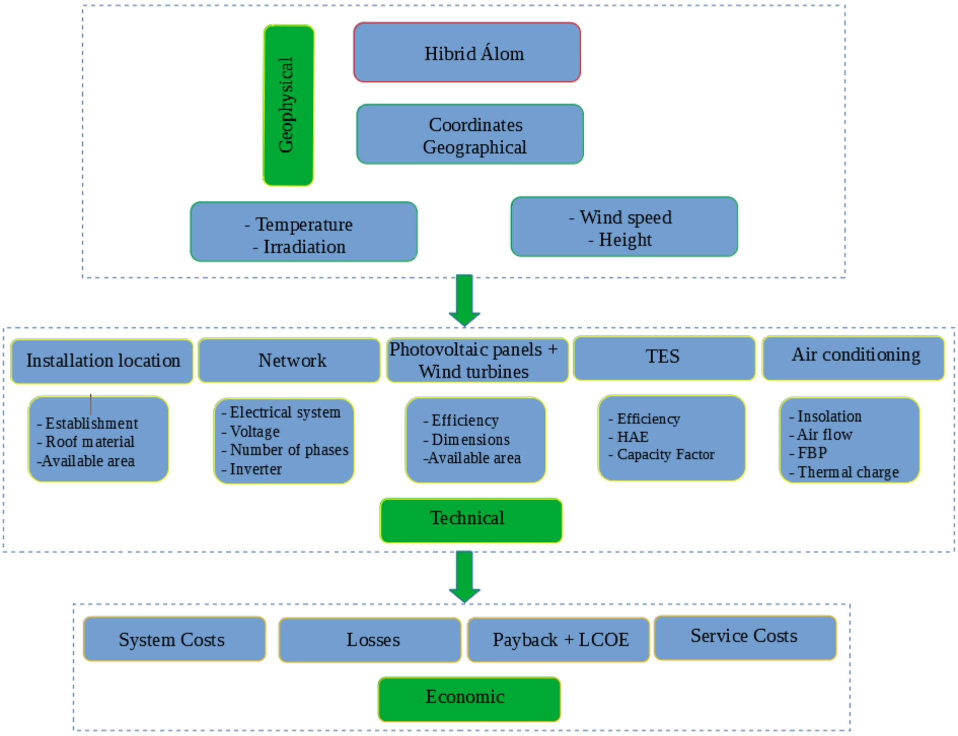
The system was developed on a Windows (Microsoft) platform with the Visual Studio Code (VSC) tool. The main programming languages used were Python, JavaScript and CSS. In order to satisfy the load demand required by the customer, the hybrid system must be dimensioned correctly, observing the characteristics of the installation site, for example: available area, load demand, environmental conditions, so that there is efficiency. Important to be considered in the HS modeling process are the energy losses during the normal operating regime, these occur in the electrical cables and in the inverter (mainly).

Figure 5. API flow interacting with simulator and end user.



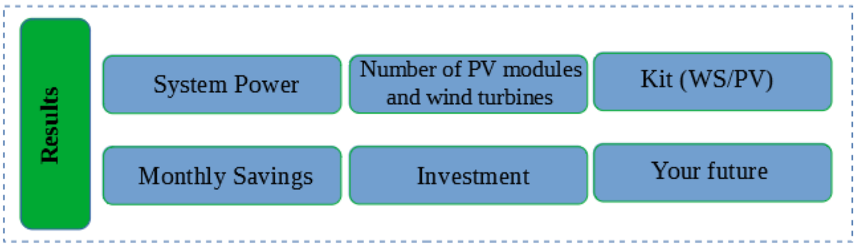
According to Posadillo et al. (2008), there are four optimization approaches in the modeling process: intuitive, analytical, numerical and intelligent methods (through artificial intelligence). The numerical method is through simulations based on calculation with the use of software, a method used in this work. In the modeling process, a work routine must be established, in order to organize the use of input parameters (inputs) and outputs (outputs). The algorithm is divided into three stages, see figure 6, according to the classification of parameters: Geophysical, Technical and Economic.

Figure 6. Schematic summary of parameters.



To model and estimate the performance of a HS, designed using the software developed in the scope of this work, the databases present in National Institute for Space Research [INPE] and National Institute of Metrology, Quality and Technology [INMET] are used. At each stage of the process, as a partial result, new inputs are launched for the next stage. At the end of the economic stage, where the financial analysis takes place, the results are obtained for the user's final analysis. A summary of the results obtained can be seen in Figure 7.

Figure 7. Results of the simulation process.



3.1 Performance of the wind and photovoltaic system

To calculate the energy that can be extracted from a given air mass by an aerogenerator, first calculate the amount of kinetic energy contained in said air mass, through the equation of energy potential.The German researcher Albert Betz (1919) created hypotheses that demonstrate, through the principles of conservation of mass and energy, the efficiency limit of a wind turbine, in the same way that combustion engines do not make full use of thermal energy (Carnot cycle) as they reject part of the heat to the environment, the wind turbine rotor is also incapable of transforming the entire movement of the air mass into energy (RAGHEB and RAGHEB, 2011). Through the analysis of the available air mass speed (v1), the speed resulting from the interaction with the rotor (v2) and the air current speed after the interaction with the generator (v3), it is possible to observe how much of this kinetic energy was used and how much it followed as natural air flow (RAGHEB and RAGHEB, 2011). Figure 8 shows part of the script which contains the processing logic for the wind turbines, taking into account the geophysical data linked to the latitude and longitude of the system user.

Figure 8. Script for calculating available power by wind turbine diameter.

```
## DImensionamento Aerogeradores
    #Medicação do vento

        import requests as rt
        import re # Regular expression library (Regex)
        import numpy as np

            v1 = tempoemhoras*velocidademedida;
            v2 = velocidade*(720-tempoemhoras);
            user_veloc = (valorum+valordois)/720;
            area_inic=(cargareal*1000/720)/((Math.pow(velocidade,3))*0.5*1.23*0.59);
            area_fin=(ValorCargaMedia*1000/720)/((Math.pow(velocidade,3))*0.5*1.23*0.59);
            area_ag_1=(cargareal*1000/720)/((Math.pow(user_veloc, 3))*0.5*1.23*0.59);
            area_ag_2=(ValorCargaMedia*1000/720)/((Math.pow(user_veloc, 3))*0.5*1.23*0.59);

            if (ValorCargaMedia==0.0) {area_ag = area_ag_1;}
            else{area_ag = area_ag_2;}


            dim_aeroger = area_ag.toFixed(2);
            formulario.dim_aeroger.value = dim_aeroger + '\ m²';
            diametro_aerogeradoro = 2*(Math.sqrt((dim_aeroger)/3.1416));

        return (diametro_aerogerador)
```

The simulations carried out so far return with dimensions for a nominal turbine that would supply part of the user's demand. However, there are turbines with their own dimensions and characteristics on the market.The main indicator that differentiates one turbine from another, adopted in this research, is the diameter of the rotor. The diameter of the rotor (twice the length of the blade) determines the amount of energy that the generator will be able to convert, to know how much energy this turbine will supply, that is, what percentage it will supply, what investment is required and information on the financial return on the investment.

As noted by Kathib et al. 2013, the performance of the photovoltaic module mainly depends on the conditions of sunlight and cell temperature. It is not the aim of this work to detail the physical and chemical theory behind photovoltaic conversion, however more details can be found in Bayod-Rújula et al. (2019). There are currently different technologies available on the market, with the use of different materials for the manufacture of photovoltaic cells. Crystalline silicon cells (c-Si) dominate the market because there is a solid knowledge of the production technology and abundance of the material - silicon, as presented in the study by L. V. Mercaldo and P. Delli, (2020). The photovoltaic cell is the basic element of technology for converting sunlight into electricity, the union of cells connected in series constitute the PV modules, as shown by Tian et al. 2012, therefore, the electrical characteristics of the modules are determined by the electrical characteristics of the cells.At this stage of the process, other technical factors that add associated losses are also calculated, such as: Inverter, electrical and protection devices, cabling and so on.

To estimate the performance of the system, in addition to the points mentioned and evaluated, there are other loss parameters, such as shading, dirt and losses in transformers, but such situations will not be addressed in detail, they are beyond the objectives proposed in this phase and identified as points of future work. Figure 9 shows part of the script which contains the processing logic for the PV modules, taking into account the geophysical data linked to the latitude and longitude of the system user.

Figure 9. Available power calculation script based on geophysical data.

```
## Cálculo da energia disponível, após subtração das perdas na potência

        import scipy.integrate as integrate
        import numpy as np

        def fcn_ener_final(Pot):
        energ_dispo = integrate.trapz(Pot,dx=1,axis=1)

        check_dict = {1: range(0,31), 2:range(31,59), 3:range(59,90), 4
        :range(90,120), 5:range(120,151), 6:range(151,181),
        7:range(181,212), 8:range(212,243), 9:range(243,273), 10:ra
        nge(273,304), 11:range(304,334), 12:range(334,365)}

        energ_dispo_end = []
        for i in range(1,13):
        c = np.round(np.sum(energ_dispo[check_dict[i]]),2)
        energ_dispo_end.append(c)


        return energ_dispo_end
```

3.2 Thermal Energy Storage (TES)

One of the bottlenecks to wider deployment of renewable energy is the development of efficient energy storage systems that can compensate for the intermittency of renewable energy sources. Thermal energy storage (TES) is a very recent technology that can be a promising and location-independent alternative for energy storage, without the corresponding geological and environmental restrictions.

One of the alternatives used by hybrid plants to increase the capacity factor is (TES). Through these systems it is possible to correct asymmetries between the supply and demand of electricity. In the case of the Brazilian market, where a differentiated tariff in relation to time is not practiced, thermal storage will only benefit the plant if the capacity factor is increased. Unlike other markets, where plants are rewarded when they generate electricity during peak demand, making them more competitive.

The increase in the plant's generating capacity can be achieved through the correct dimensioning of the thermal storage system. According to Cardemil et al (2010), the TES dimensioning is determined by a parameter called hours of equivalent storage (HAE), which was defined as the storage energy required to ensure the operating energy of a power cycle during one hour, for the nominal design conditions. A plant with TES operating under a configuration known internationally as a two-reservoir configuration is defined. The storage fluid is a salt of known composition, composed of 60% $NaNO_3$ and 40% KNO_3. In this analysis, thermal losses in the reservoirs are not considered.

3.3 Financial analysis

To verify whether a technology is an economically viable investment, it is necessary to resort to the use of analysis models that assess both the investment costs and its implicit benefits, indicating which economic benefit may or may not be obtained. At this stage of project modeling, the user enters the costs involved in his/her residence/establishment, and as a result, the financial analysis parameters are obtained, as well as the cash flow for the lifetime of the project. It is necessary to be clear about the need for greater rigor in the survey of costs (budget) in order to carry out simulations with real values for each region and/or installer and not the averages applied in the market. However, the possibility of viewing the information necessary to make a decision to invest or not in a HS for self-consumption is demonstrated.

The cash flow is outputted by the project lifetime, total energy forecast for each year (corrected by the efficiency loss index), operation and maintenance costs, LCOE and return on investment (payback).

4 RESULTS AND DISCUSSION

According to the objectives established in this work: to study and evaluate the essential aspects for the development of a Hybrid system project, a dimensioning and simulation tool was developed, where it is possible to evaluate the technical and economic feasibility for each local reality. An important aspect, remaining as a future objective, is the development of simulations that consider the effects of complex shading, because in urban areas, where there are physical space limitations, shading has a great impact on energy losses. This is a difficult simulation parameter, for which current simulation softwares present simplified solutions, not representative of the complexity of urban built architecture and, consequently, complex shading.

In order to assess the feasibility and test the reliability of the calculation routine of a small-scale hybrid wind-photovoltaic system, an already installed hybrid plant was analyzed, relating it to the simulation result in the system developed in the scope of this work. , for the same location.

The hybrid EO/FV off-grid plant is located in the municipality of Botucatu in São Paulo in the geographic location defined by coordinates 22° 51' South Latitude (S) and 48° 26' West Longitude (W) and average altitude of 786 meters above at the sea level. The monthly average wind speed at a height of 10 meters is 3.1 m/s and the daily average monthly global solar energy is 4772.13 Whm-2. Plant with an average monthly consumption of approximately 200 kWh, at a cost of R$ 0.80/KWh.

The results of the hybrid plant already installed are presented by Silva (2010), it is observed that the hybrid energy did not show variations proportional to the variations that occurred in the available solar and wind energy. However, they show a similar behavior in relation to the seasons of the year, with the winter and autumn seasons providing higher levels of available energy generated by the hybrid system in the analyzed location.

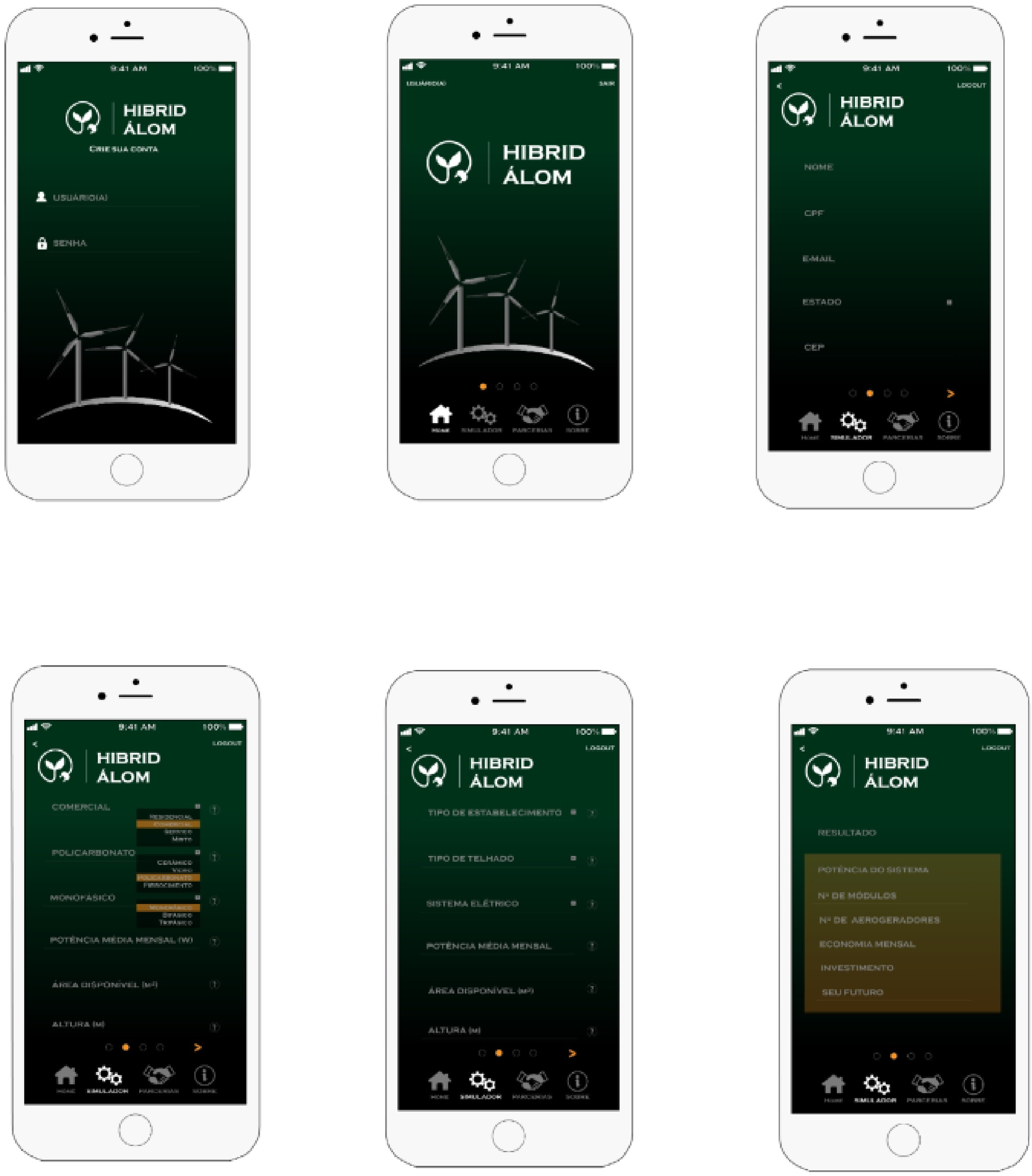
Table 1 presents a series of data that allows for a comparative analysis between the two systems mentioned above. We can see that the result has a slight discrepancy, which confirms the consistency in the calculation routine of the developed system.

Table 1. Comparative complementarity analysis between existing system and Hibrid Álom simulation

	Installed System	**Simulated Hibrid Álom**
Wind turbines Ø	1,15 m	1m - 1,5m
Solar panels	3	4
Amount	-	R$ 15590,72
Payback	-	7,3 anos
LCOE	0,60 - 0,80 R$/kwh	0,85 R$/kwh

Another option to be explored is related to the user's accessibility to this type of software, currently maximized for tools available online, in which any user can run simulations with the aim of evaluating the possibility of installing their own EO/FV plant for self-consumption. In short, given the potential complexity of modeling for a photovoltaic system simulation software, simplifications were selected that would allow to achieve this goal in a timely manner, but it is recognized that there are several important simulation options to add and validate, such as photovoltaic systems. solar tracking, modeling of bifacial photovoltaic modules, systems with multiple simultaneous slopes/azimuths, etc. This was, however, an important initial step, with validated results, which from energy simulation or economic simulation, have great potential for future development. Figure 10 below shows some screens of the developed Hibrid Álom application, aiming to demonstrate its layout, necessary parameters and HS outputs.

Figure 10. Hibrid Álom application flow screens (Portuguese version).



Estudo da viabilidade econômica e disponibilidade energética de sistemas de refrigeração a energia híbrida- solar / eólica com armazenamento de energia térmica

RESUMO

Grande parcela da energia consumida em todo o mundo é usada para aquecimento e resfriamento de ambientes. No Brasil, o uso de energia solar nas residências experimenta uma curva crescente, não obstante ao fato de que nem sempre um sistema exclusivamente solar possa para atender toda a demanda energética, uma vez que as condições climáticas influenciam significativamente a geração de energia e a sua eficiência energética. Sendo assim, é recomendável que se tenha alternativas para garantir ao longo do ano as necessidades energéticas nos pontos de consumo. Neste contexto, com a intenção de aprofundar as questões envolvendo a complexidade contida na compreensão e quantificação (energética e orçamentária) de projetos de sistemas construídos – ou a serem construídos - de refrigeração baseados na utilização de energia híbrida, o presente trabalho tem por objetivo o dimensionamento de um simulador online para auxiliar o desenvolvimento de projetos para instalação de sistemas fotovoltaicos e eólicos em residências, comércios e indústrias. Ademais, o estudo visa entregar projetos diferenciados e personalizados, conciliando boa eficiência e custo de operação mais reduzido. Este simulador (site/aplicativo) utiliza api (Application Programming Interface), integrando scripts programados em Python às ramificações da plataforma, de modo a oferecer, em uma única plataforma Web, a simulação completa do projeto de painéis solares e aerogeradores, orçamento, indicações de fornecedores, prestadores de serviço e estimativa da potência produzida. Os dados de Input são: posição geográfica (altitude e longitude), área disponível (m2), material do telhado (cerâmica, policarbonato, vidro e etc), altura da edificação (m), dados históricos de incidência solar e eólica (coletados dos sites INMET e INPE, respectivamente) e média mensal dos últimos anos da potência consumida (kwh). Os dados de Output são: estimativa da potência produzida pelo sistema e análise econômica, número de painéis e aerogeradores necessário para produzir a potência necessária, focando no armazenamento via TES (Thermal energy storage), bem como o impacto do estudo nas análises econômicas e energéticas do sistema.

PALAVRAS-CHAVE: Sistemas de Refrigeração; Energia Híbrida-Solar/Eólica; API; Armazenamento de Energia Térmica.

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