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CUBAN ENERGY SYSTEM DEVELOPMENT

– Technological Challenges and Possibilities

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TABLE OF CONTENTS

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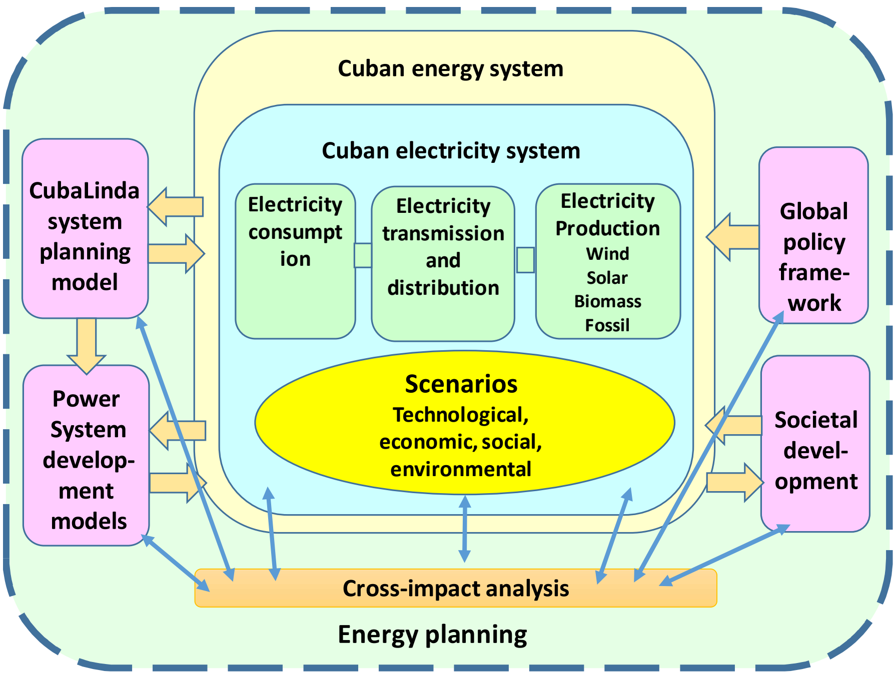
Foreword

This book is an outcome of research work carried out in cooperation with Finnish and Cuban researchers in a research project "Cuban energy transformation. Integration of renewable intermittent sources in the power system (IRIS)". The project is funded by the Academy of Finland for the period of 1.1.2019 - 31.12.2022. The objectives of the project are:

- ✓ Develop a scenario construction tool for Cuban future energy development analysis and scenario building (CubaLinda) and carry out comparison with other international energy planning models.
- ✓ Develop planning tools for integration of intermittent renewable energy sources (wind, solar, biomass) in the Cuban electricity system and improving energy efficiency.
- ✓ Develop planning tools for grid development in Cuba in order to be able to integrate the distributed intermittent renewable energy sources in the system and to improve the system efficiency.
- ✓ In a participatory workshop process, develop transformative future scenarios for Cuban energy system, acknowledging their societal impacts in the context of inclusive and sustainable development.
- ✓ Carry out cross-impact analysis of interlinkages of Cuban energy system in PESTEC framework (PESTEC = Political, Economic, Social, Technical, Environmental, Cultural).
- ✓ Develop the research capacity in the participating Cuban institutions and link them better with national energy sector actors and decision makers.

A general view of the project is illustrated in the following figure.



The participating researchers come from two Finnish universities and several Cuban universities and research centres:

University of Turku (coordinator), Tampere University, University of Oriente (Santiago de Cuba), Technological University of Havana (CUJAE), Moa University, University of Pinar del Rio, University of Camagüey, Pontificia Universidad Católica de Chile, Universidad Central "Marta Abreu" de Las Villas, University of Sancti Spíritus "José Martí Pérez", and CIES (Solar Research Centre) and CUBAENERGIA.

I. Introduction

I.1. The Challenge - The Cuban energy system development

Jyrki Luukkanen

This book about the Cuban energy system development, its technological challenges and future possibilities is a result of research work carried out in a project "Cuban energy transformation. Integration of renewable intermittent sources in the power system (IRIS)". The project is financed by the Academy of Finland.

Under President Raúl Castro Ruz (2008-18) and Miguel Díaz-Canel (since 2018), Cuba has been undergoing a slow, but constant transformation process. It is seeking to uphold its political system and the achievements of the revolution, such as universal free healthcare and education while modernising and adapting to a range of development challenges. One of the key sectors for modernisation and restructuring is the energy sector. Including growing costs and the burdens of reducing Greenhouse Gas (GHG) emissions under the Paris Agreement, Cuba urgently needs to reduce its high dependency on imported fossil fuels for electricity generation while also safeguarding domestic financial resources. These specific strategic development factors continue to hamper social and economic development and are consequently a core challenge to public policy. The government is increasingly aware that the energy problem can only be solved by dealing with both sides of the same coin: the usage of its own indigenous renewable energy (RE) sources on one side and, in parallel, implementing energy-efficient technologies and changing the way energy is being utilised in all sectors of the society.

The current Cuban energy profile reveals a high dependency on fossil fuels and the high cost of energy delivered to final consumers. It has become clear that there is a problem of low efficiency through the value-chain from production to distribution and consumption. A trilemma of; i) improving energy security, ii) reducing costs and iii) reducing GHG emissions and environmental impacts is clear. Energy, socio-economic development, and the environment have been given a high priority in national development plans. Abundant domestic resources (solar, wind and biomass) could resolve the issues of dependency, costs, emissions, delivery, and access, and would necessitate the modernisation of systems, but their utilization requires large investments. Cuba wishes to attract foreign investors with the new investment law.

Cuban power generation delivered from wind power (WP) and Solar Photovoltaic (SPV) currently represents just 4 % of the produced electricity. The government plans to reach 24 % by 2030 coming from increasing wind power, solar photovoltaic, biomass and small hydro. By 2030, the plan would increase wind power capacity to 656 MW, solar power capacity to 700 MW, biomass capacity to 872 MW, and small hydropower capacity to 56 MW. The Ministry of Energy and Mines (MINEM) is willing to increase the target of renewable energy sources for electricity generation to 29% for the year 2025. This would lead to a power system network with large, distributed generation penetration. Cuba has an isolated power system, and key issues of stability, security and reliability of power system network will inevitably arise with the integration of large shares of such intermittent generation.

There are several co-benefits in developing the Cuban energy system more based on renewable and sustainable sources. Firstly, the reliance on Venezuelan fossil imports raises a significant question on reliability and vulnerability of resources in the time on political turbulence and Venezuelan economics. Diversification of the energy production mix and domestic production have both notable employment opportunities and also decrease dependency on imports. Due to the new investment law Cuba is starting to attract international investors but must be cautious with the sustainable governance of natural resource extraction and land use. Cuba is simultaneously highly vulnerable to climate change impacts such as Caribbean hurricanes and sea-level rise and needs to develop the whole sector consistently with energy independence and resilience in mind. Decentralised and modernised systems are less prone to power cuts and more adaptable to disasters. Furthermore, there are still rural off-grid regions in Cuba and thus a decentralised energy system based on self-sufficient sustainable sources will have a direct link to equitable energy access and socio-economic development for the poorest people in the country. Rural employment creation is also a national economic asset.

In terms of global politics and international cooperation in times of climate change, the current energy transition in Cuba incorporates several challenges but also possibilities. The orientation towards renewables and improved efficiency can decrease the emission of greenhouse gases and increase energy security – due to the process of decentralization of energy production. Decentralisation and diversification might both contribute to energy security as well as to more environmentally friendly energy production. Decreasing international dependence should cover the dimension of technology: the dependence on oil imports should not be replaced by a new international dependency on imports of high technologies.

However, it has also been often noted that a considerable increase in the supply of intermittent renewable energy sources (solar and wind) can cause technical problems related to the control of supply-demand balance in the electricity system. This must be taken into account in the electricity system planning, including hourly and seasonal variations in supply as well as electricity demand. The issues related to the power system state estimation, frequency control, operational reliability of power plants, optimisation of distribution and transmission grid, prediction of photovoltaic production and biomass thermal conversion in the context of increased distributed intermittent power production have to be taken into account in the system planning.

Power systems evolution towards high penetration of renewable production has been under extensive research already for years. Smart grids distributed renewable generation systems, energy storages, switching power converters, etc. have been the most popular topics in recent engineering-related conferences. So far, this new approach has been investigated in some limited districts connected as a part of the bigger conventional system and not much research exists on the integration of intermittent renewable energy in the Cuban grid. With the high penetration of renewable generations in the distribution network; the power network is no more passive, as such, the power flow and voltage profile are determined by both generation and load. These cause new challenges to the distribution system over centralized predictable and dispatchable production due to the intermittency and fluctuating characteristics. The integration of renewable generations into the distribution network close to customers reduces transmission cost, power loss and capacity. However, renewable generation output is influenced by meteorological conditions. Thus, the Cuban network operating system must be revisited and controlled in a more innovative manner, minimizing the losses and maximizing reliability. This is why new research is needed on dynamic planning of the integration of intermittent renewable sources and related configuration of transmission and distribution networks.

Electricity production in Cuba relies mainly on the combustion of fossil oil and gas in the power plants. The so-called termoelectricas, condensing steam power plants producing the base-load are considerably old and suffer from time to time component breakage causing problems for the electricity supply. The problems with the oil imports, enlarged by the US economic blockade, have made it difficult to maintain the necessary storages of oil for the distributed generators in order to compensate for the power shortage from the centralised system during equipment breakage. This has resulted in blackouts when enough capacity is not always immediately available.

The research work for this book has been carried out in the IRIS project in different participating universities and research institutions. Finland Futures Research Centre of the University of Turku is the coordinating organisation for the IRIS project. Two faculties from Tampere University are involved in the project; Faculty of Engineering and Natural Sciences and its Automation Technology and Mechanical Engineering, Process Automation research group as well as Faculty of Information Technology and Communications Sciences and its research group of Electrical Engineering.

Cuban participants in the IRIS project and contributors to this book include Universidad de Oriente (UO), Facultad de Ingeneria Eléctrica and Facultad de Ingeniería Mecánica e Industrial; CUJAE (Technological University of Havana) and its Faculty of Electrical Engineering with the Centro de Investigaciones y Pruebas Electroenergéticas, CIPEL; University of Moa; CUBAENERGIA and Centro de Investigacion de Energia Solar (CIES) under the Ministry of Science, Technology and Environment of Cuba.

The IRIS research project has made it possible for researchers to network, collect and exchange information, get acquainted with the new research results and methods, learn to use new research techniques and software and laboratory equipment. Visits of the research personnel in the participating universities, research institutes, energy companies and conferences have made the information exchange possible.

The IRIS project has built on the work carried out in capacity building projects. PROCEED-CARIBBEAN, Promotion of Capacity and Energy Education Development in the Caribbean Region was financed by EU EDULINK programme and coordinated by Finland Futures Research Centre. CRECE, Capacity Building for Renewable Energy Planning in Cuban Higher Education Institutions was financed by ERASMUS+ programme and coordinated by Finland Futures Research Centre. Tampere University and Cuban universities were partners in these projects.

This book deals with the technological aspects related to the Cuban energy system. The sister book “Cuban Energy Futures. The transition towards a renewable energy system – Political, Economic, Social and Environmental Factors" deals with the socio-economic and political aspects of the Cuban energy system. This book "Cuban energy system development – Technological challenges and possibilities" provides general articles on the energy system and contributions from 19 Cuban PhD researchers who shortly introduce their research topics. In this book, we first discuss generally the energy economy and challenges of planning in Cuba and provide an outlook into the historical development of energy production and consumption in Cuba.

The next section looks at the electricity grid development in Cuba. Introduction to this section is provided by Ariel Santos Fuentefria, Miriam Lourdes, Irina Salazar, Sami Repo, Miguel Castro Fernández. The history and future development needs of the electricity grid are discussed by Miguel Castro Fernández and Miriam Vilaragut Llanes. Next, the challenges in the integration of electricity produced with renewable energy sources are discussed by Ariel Santos Fuentefria and Yrjö Majanne. Finally, the operation and control of the Cuban power system is presented by Antonio Martínez García, Miriam Vilaragut Llanes, Miguel Castro Fernández, Ariel Santos Fuentefria and Yrjö Majanne.

The following section looks at the energy resources in Cuba. The introduction to energy resources is written by Luis Vázquez Seisdedos, Miriam Vilaragut Llanes and Yrjö Majanne. First, the wind energy potential in Cuba is discussed by Conrado Morena and Miguel Castro Fernández. Solar photovoltaic energy potential in Cuba and the related challenges are presented by Ruben Ramos Heredia, José Emilio Camejo Cuán and Saddid Lamar Carbonell. Biomass energy resources, technologies, current situation and future perspectives are presented by Jorge Jadid Tamayo Pacheco, Angel Rubio Gonzales, Lorenzo Llanes Junior and Angel Luis Brito Sauvanell. The role of hydropower in the Cuban electricity system and the future plans are discussed by Leonardo Peña Pupo, Ernesto Yoel Fariñas Wong and Angel Luis Brito Sauvanell. Next, the energy storage and related technologies and applications in Cuba's electricity grid is discussed by Miguel Castro Fernández, Rafael Pomares Tabares and Miriam Vilaragut Llanes.

Conclusions of the topics presented in the book are drawn by Jyrki Luukkanen.

II. Energy economy and challenges of planning

II.1. Introduction

Jyrki Luukkanen

The historical development in the Cuban energy sector forms the basis for new development. The global changes and changes in Cuban society form the framework for the changing energy system. Historically the main driving forces in energy system planning have been the dependence on fossil fuels, both on imported oil and its derivatives, and the national production of fossil energy - crude oil and natural gas. Biomass has been an important energy source in the form of bagasse which has been widely utilized in the sugar industry for the production of electricity and heat for the sugar manufacturing process.

There is, however, an urgent need for a change in the energy system. There are different economic drivers underlining the need for change. The increasing costs of fossil energy is one driver requiring a reduction in the import of fossil energy. The technological development and the resultant decrease in the price of renewable energy production is an important factor behind the changes enabling investments in solar PV and wind energy technology.

The environmental reasons for the change are significant. The international climate policy and the needed mitigation and adaptation efforts are important drivers for change. The increasing role of renewable energy in the reduction of CO_2 emissions will cause a major change in the electricity systems worldwide and in the Cuban electricity system. In addition, controlling pollution from energy production at the local level requires changes in energy technology

Since 2014, the Cuban government has promoted the development of renewable sources and the efficient use of energy in the country. The regulations to carry out this process are established in Decree-Law 345 of 2019 of the State Council, which provides for contributing to increasing the participation of renewable energy sources in the generation of electricity; progressively replacing fossil fuels; increasing efficiency; saving energy; as well as stimulating investment and research in the field of renewable sources, among other objectives.

According to this decree-law, the maximum participation of Renewable Energy Sources in the Cuban National Electricity System and the increase of energy efficiency demands have the following requirements: the optimal use of the advantages of distributed generation, since generation close to consumption minimizes losses in the electrical networks; the increase of cogeneration that implies the simultaneous generation of electric energy and heat; the adaptation of the National Electric System to the new operating conditions; the adoption of measures to flatten the load curve of the National Electric System; and the use of energy storage technologies.

Sustainable development of electricity production requires a very large-scale penetration of wind and solar power, which are highly intermittent and non - dispatchable energy sources. The variable properties of the renewable sources will require a change in the planning and the management of the electricity system.

The current, centralised electricity generation will be changing to include more distributed generation which will require changes both in the local and regional management and governance system as well as in the planning of the technological system to respond to the needs of reliability, efficiency, and cost-effectiveness of the system.

Changes in the governance system are needed in the transition process including changes in the organizations and responsibilities, and legislation and regulation supporting the transition. The transition process should be organized so that decentralized decisions and interactions between stakeholders finally converse to a solution that is continuously evolving. Stakeholder interactions have the potential for synergy benefits, but there are also risks for conflict-of-interests if not properly coordinated. For example, there are several competing and interacting investments to transfer the electricity system to carbon neutrality. The risk of incorrect investments for future needs is relatively high due to uncertainty that is delaying the investments and the evolution of stakeholders. The cooperation and coordination consist of multiple elements from political decisions and societal aspects to techno-economical decisions and solutions. The aim should be to combine all these aspects to a planning methodology to enable enhanced cooperation and coordination between stakeholders and to find the best possible combined solution.

In this section first, the historical development of Cuban energy production and consumption is analysed. This provides a wider framework for the detailed analysis of the different aspects of the change by the work of the PhD researchers and group of specialists and researchers.

Next, *Anaely Saunders Vazquez* investigates the management of the energy system at the local level. Her research focuses on the development of a system for the management of knowledge and innovation of territorial governments focusing on the energy economy for sustainable local development and the design and implementation of an integrated energy management and planning model to support decision-making.

Starting from better control of demand, *Saddid Lamar Carbonell* works on a method that combines the ARIMA model and artificial intelligence techniques to improve precision in demand forecasting. Short-term load forecasting has played an important role in energy supply-demand management for the efficient use of energy. However, it becomes a challenge when there is a high penetration of renewable sources into the electric grid because of their variability. The research aims to develop a short-term net-load forecasting method/methodology for distribution power systems with large-scale deployment of grid-connected solar photovoltaics.

The integration of renewable sources is not only a global problem but also a local one. In Cuba, the decision has been to connect photovoltaic solar energy in the distribution networks, in small plants up to 10 MW distributed throughout the country. It is necessary to see how these distribution networks are affected and *Irina Salazar Fonseca* has been developing a mathematical model for stochastic planning of the optimal expansion of Distribution Networks including renewable distributed generation and smart grid technologies. This study focuses on the multi-objective optimization methods where reliability, grid losses, investment costs, and uncertainties are considered.

II.2. Historical development of energy production and consumption in Cuba

Jyrki Luukkanen, Miriam Lourdes Filgueiras Sainz de Rozas, Miguel Castro Fernández, Miriam Vilaragut Llanes and Anaely Saunders Vázquez

Energy production and consumption in Cuba have changed rapidly due to the different phases of economic development. The Cuban economy grew fast after 1970 until 1990 when the collapse of the Soviet Union had a large impact on the country's economy as can be seen in Figure.1.

The figure illustrates the development of value-added in different sectors in Cuba. After 1995, the economy started to grow again and the growth was considerably intensive in early 2000. During the last couple of years, the Covid-19 pandemic and intensified US blockade on the Cuban economy have reduced the economic development, which cannot, however, be seen in the statistical figures, yet.

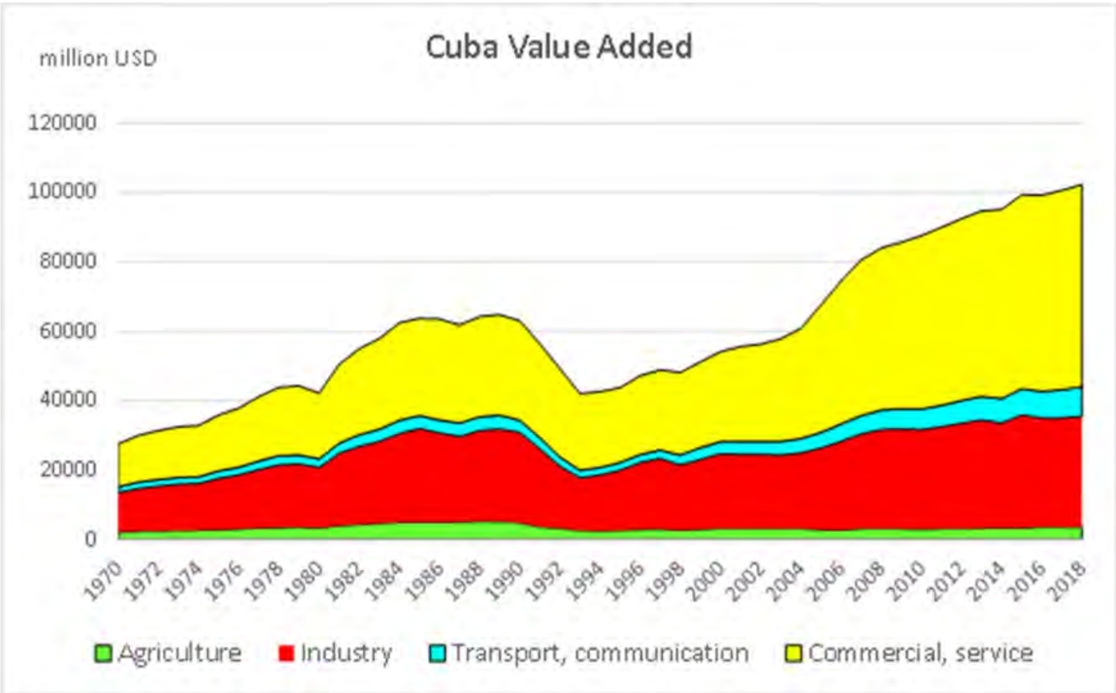


Figure 1. *Economic development in Cuba (UNStats, 2021).*

The Cuban economy has changed considerably and the domination by industrial growth has switched to domination by service sector growth (see Fig. 2). This has naturally an impact on the energy economy too because the energy intensity in different sectors of the economy is different.

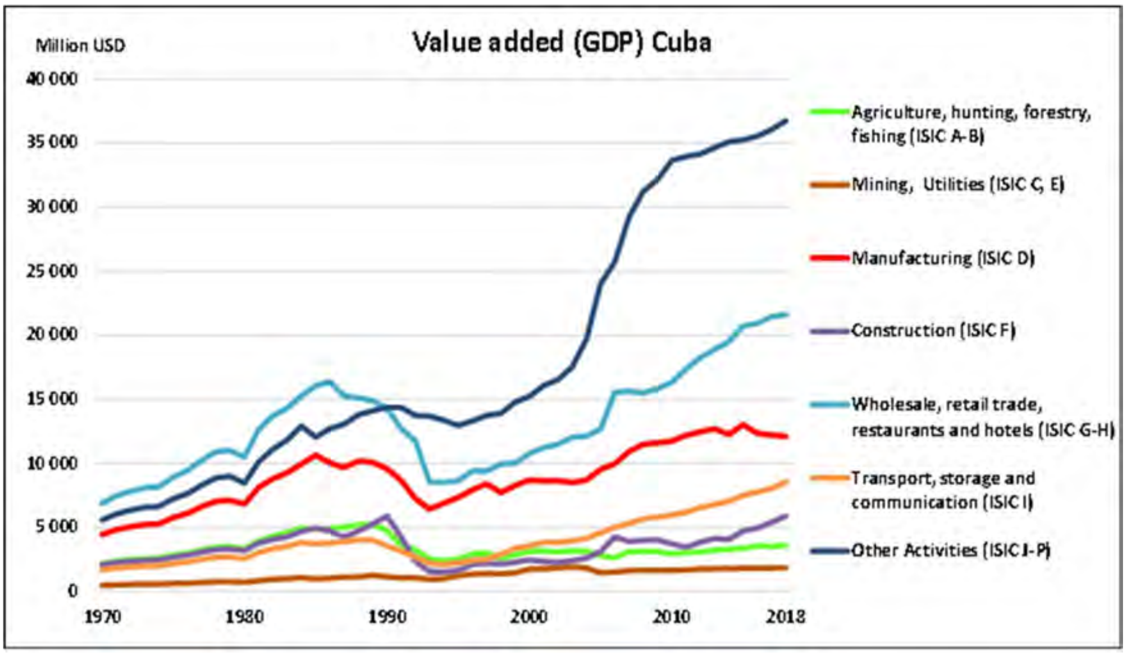


Figure 2. *Economic development in different sectors in Cuba (UNStats, 2021)*

Oil and petroleum products are the main energy source in Cuba. Cuba has domestic oil and gas reserves but the country also imports oil. Figure 3 illustrates the share of domestic oil and gas production and the imported/exported share. During 2000, a little more than one-third of oil and gas consumption was based on domestic production.

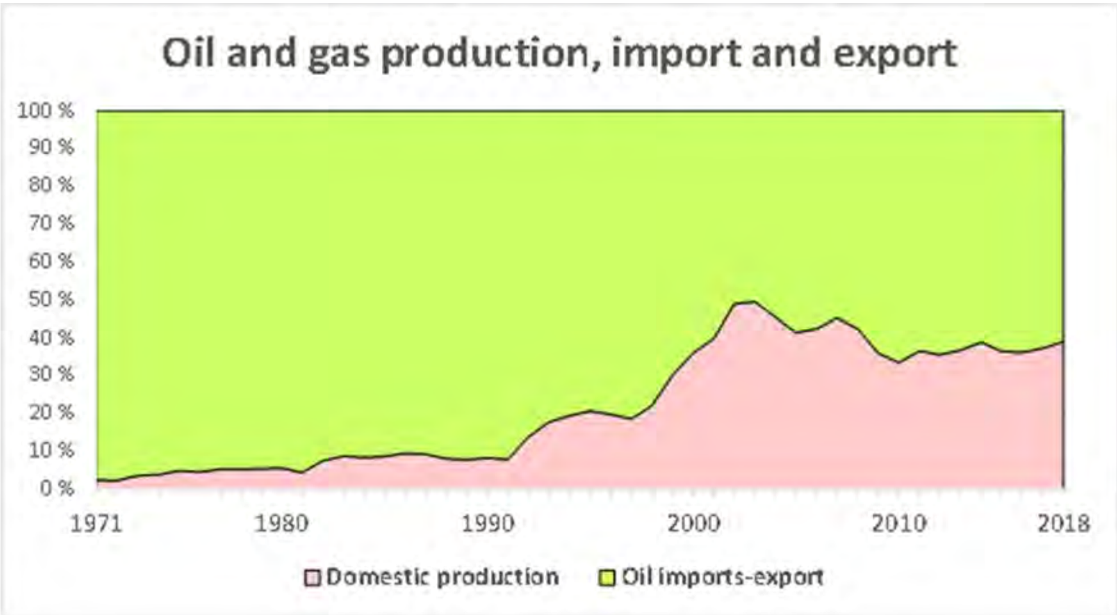


Figure 3. *Share of domestic oil and gas production and the import/export share. Data source (IEA 2020).*

The Figure 4. shows the amount of domestic oil and gas production and the net imported amount.

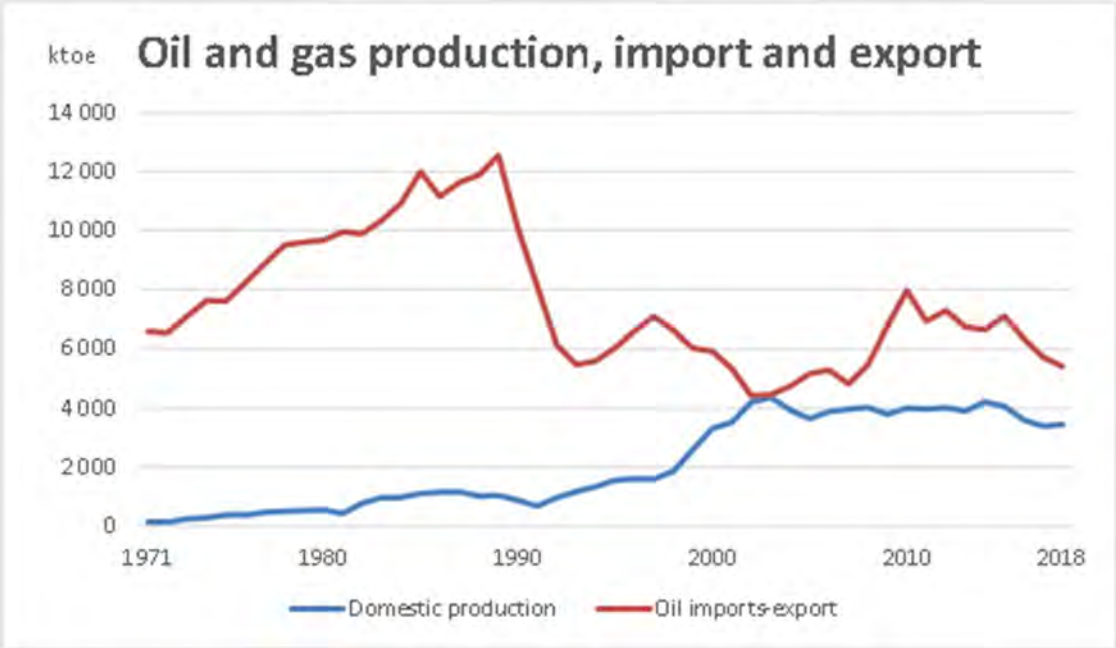


Figure 4. *Domestic oil and gas production in Cuba and the net amount of oil import. Data source (IEA, 2020).*

Figure 5 gives more detail of the oil and gas production as well as the import of crude oil and import and export of petroleum products. Data source (IEA, 2020).

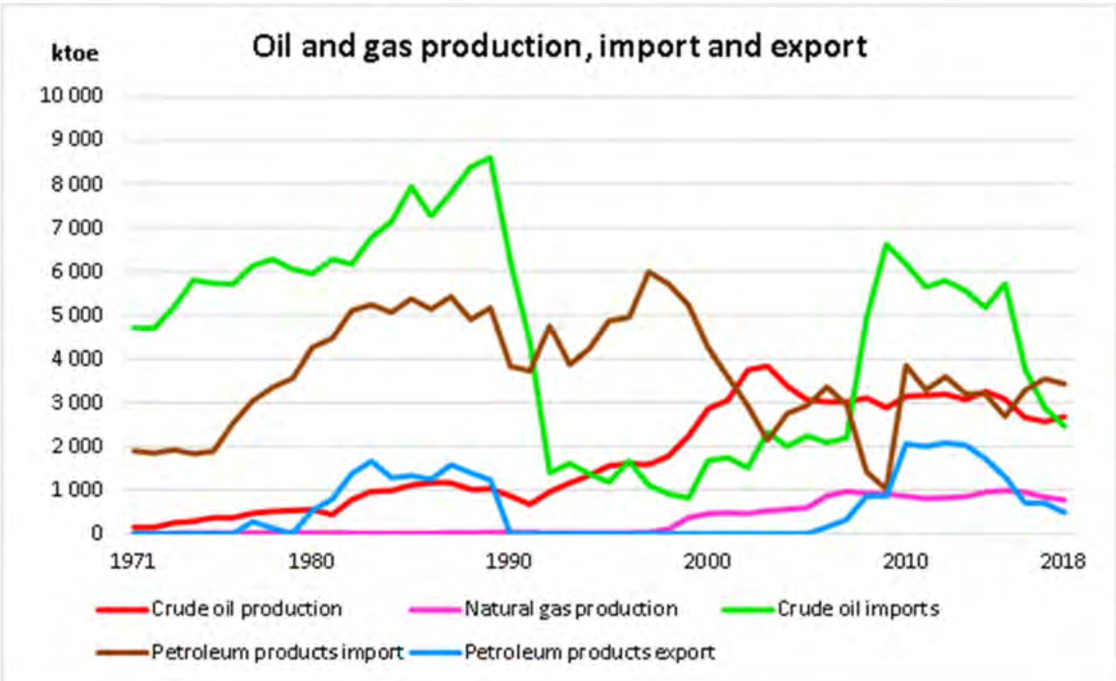


Figure 5. *Domestic oil and gas production in Cuba, import of crude oil, and import and export of petroleum products. Data source (IEA, 2020)*

The total primary energy supply in Cuba is shown in Figure 6. Here we can see that biofuels, in the case of Cuba, bagasse in the sugar industry, used to be an important source of energy up to 1990.

The reduction of sugar production as a result of reduced export has reduced the use of bagasse after 1990.

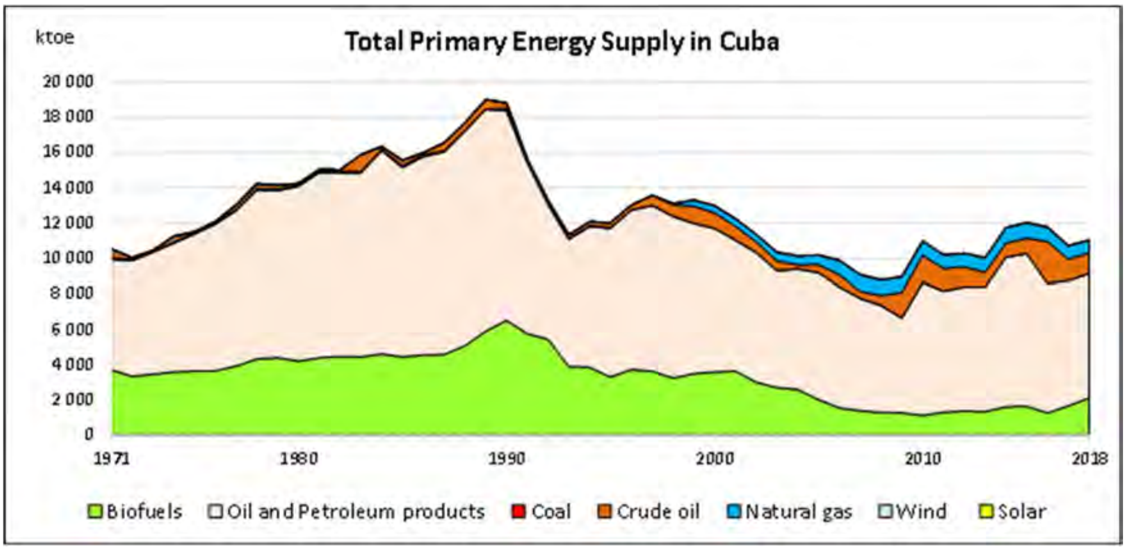


Figure 6. *Total Primary Energy Supply (TPES) in Cuba. Data source (IEA, 2020)*

The reduction in biomass use has reduced the share of renewable energy sources in the Cuban energy system and the reliance on fossil energy has increased as can be seen in Figures 7 and 8.

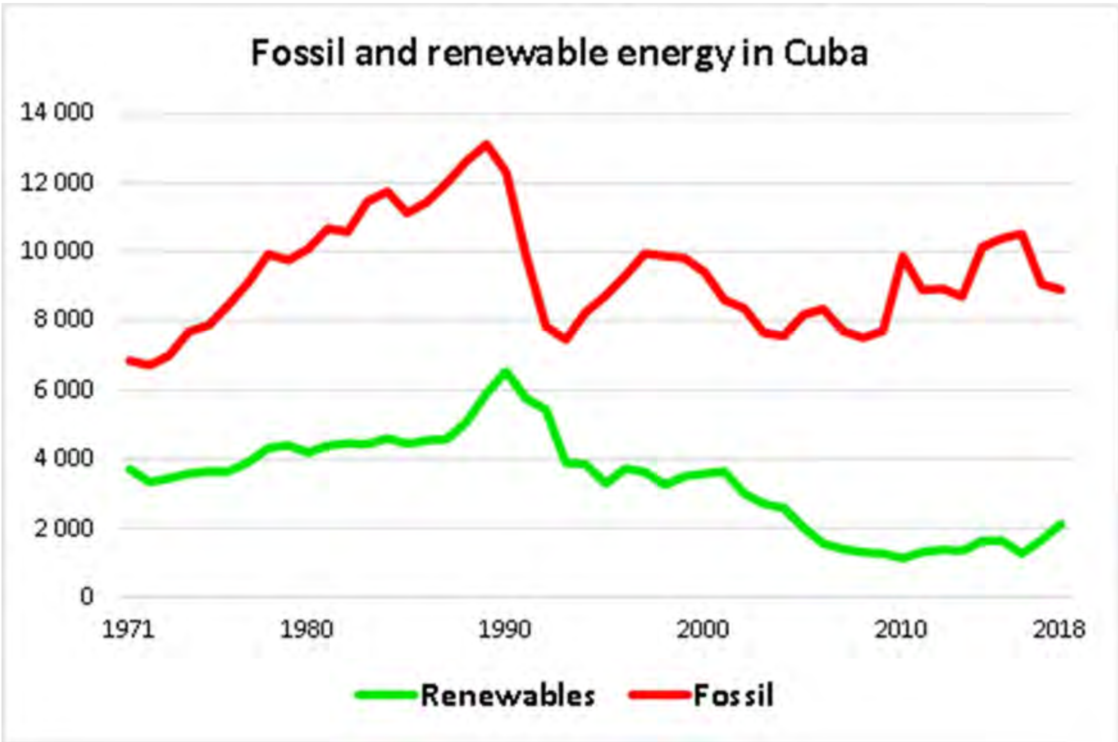


Figure 7. *The use of Renewable and Fossil energy in Cuba. Data source (IEA, 2020)*

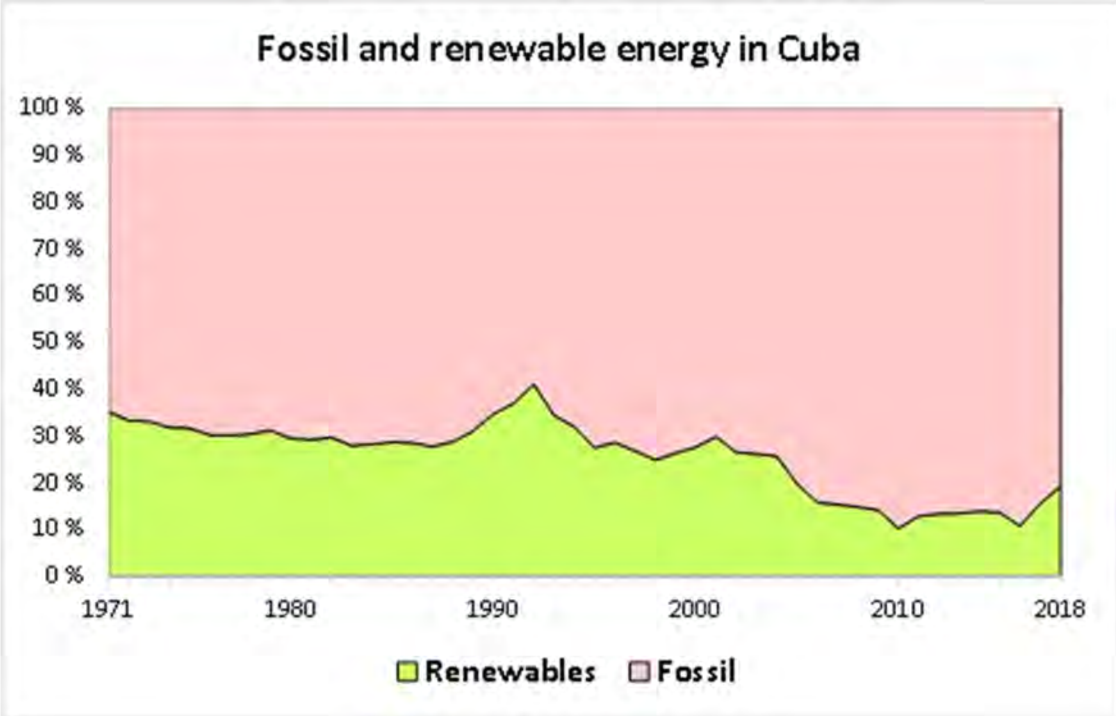


Figure 8. *Share of Renewable and Fossil energy in Cuba. Data source* (IEA, 2020)

Cuban electricity production is based on different types of power plants. Steam power plants (Termoelectricas) are the backbone of Cuban electricity production. They produced 55 % of electricity in 2018 according to ONEI statistics (See Table 1 (ONEI, 2020)). The installed capacity of diesel plants and the so-called “New technology” plants (motor plants using fuel oil) is a little bit larger than the condensing power plants but their capacity factor is lower because the termoelectricas produce the base load together with gas turbines. The hydropower capacity in Cuba is very small because there are no large rivers that could be utilized. The solar and wind power capacity is increasing and the government plans for the future include considerable increases in their capacities. The plan is to have about 800 MW of solar PV and 700 MW of wind power installed by 2030. The plan for the biomass-based capacity increase is also to about 755 MW by 2030. The new biomass-based capacity would use both bagasse and wood as the energy source. The plan is to increase the efficiency of the biomass plants by increasing the steam pressure and temperature.

Table 1. Structure of power generation in Cuba in 2019. Data source (ONEI, 2020).

Type of generation	Installed capacity MW	Production GWh	Share of production
Steam power plants (oil)	2 498	12 664	61 %
Gas turbines	580	2 450	12 %
Diesel plants and "new technology"	2 642	4 372	21 %
Hydro power	64	125	1 %
Solar and wind	159	251	1 %
Other thermal (industry)	459	842	4 %
Total	**6 508**	**20 704**	**100 %**

Electricity production in Cuba has been based mainly on oil as can be seen in Figure 9. The gas production increased in 2000 is enabling electricity production to increase with gas turbines.

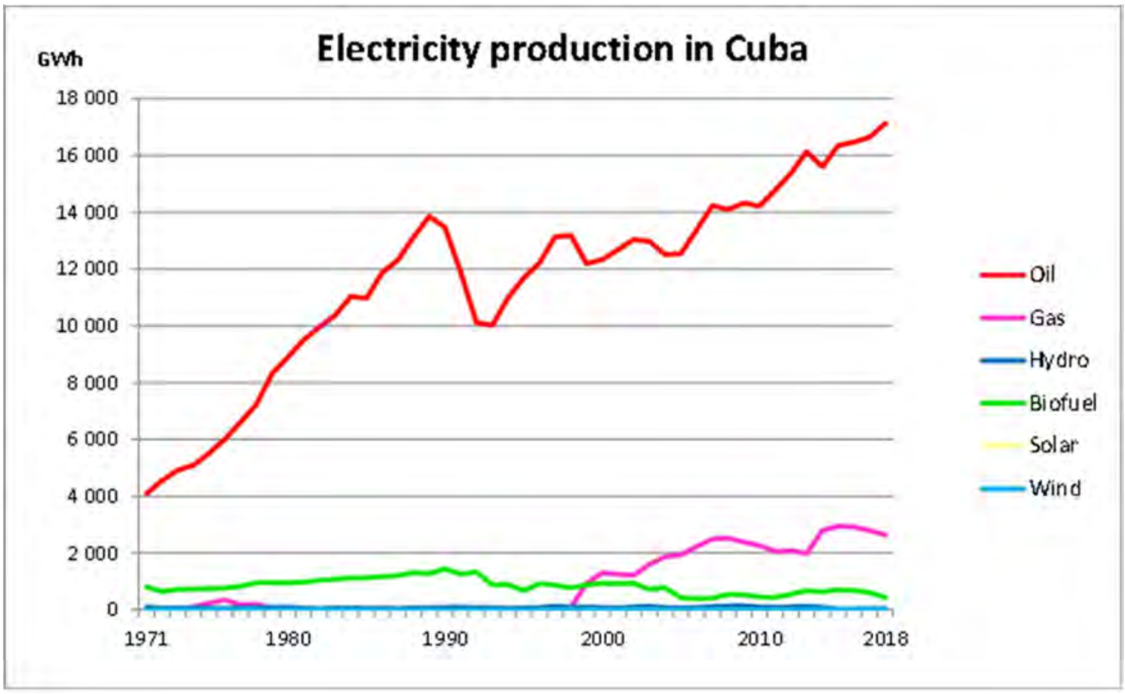


Figure 9. Energy sources for electricity production in Cuba. Data source (IEA, 2020)

Figure 10 illustrates the share of electricity produced with fossil fuels and renewable energy. The increase in wind and solar production cannot yet be seen in the figure because their share is still so small.

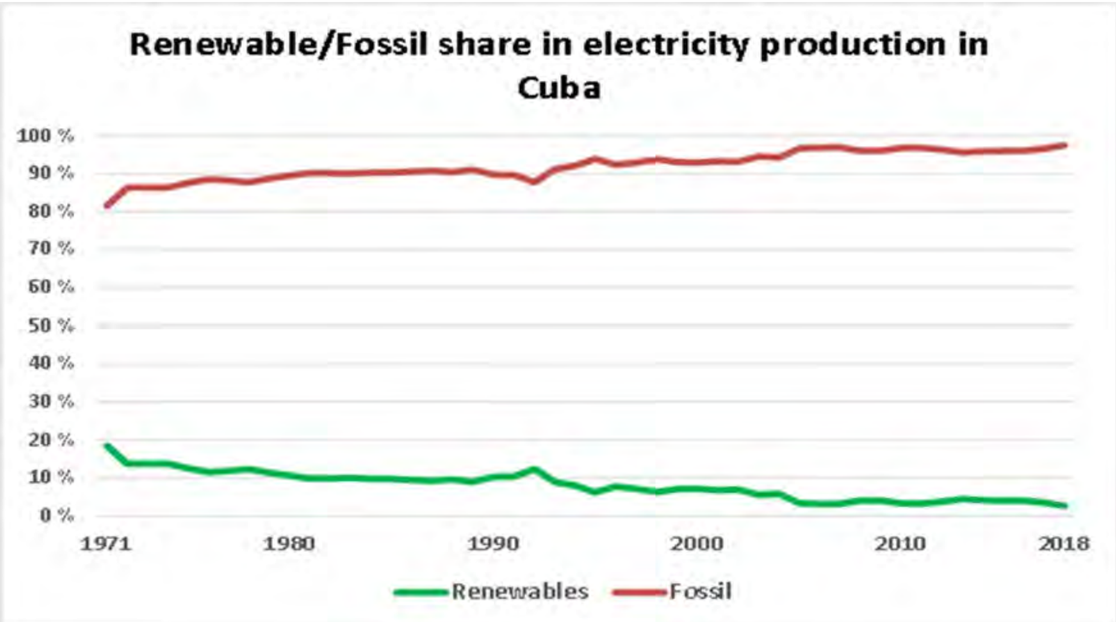


Figure 10. *Share of electricity produced with fossil energy and renewable energy in Cuba. Data source* (IEA, 2020)

Electricity consumption has increased considerably during 2000 in Cuba. The main increase has been in the residential sector. Part of the residential sector consumption should be allocated to the service sector because the statistics do not differentiate the consumption in the so-called 'casas particulares' which serve as accommodation for tourists. Industrial electricity consumption used to dominate the consumption sector but its electricity consumption has not increased after 1990 as can be seen in Figure 12.

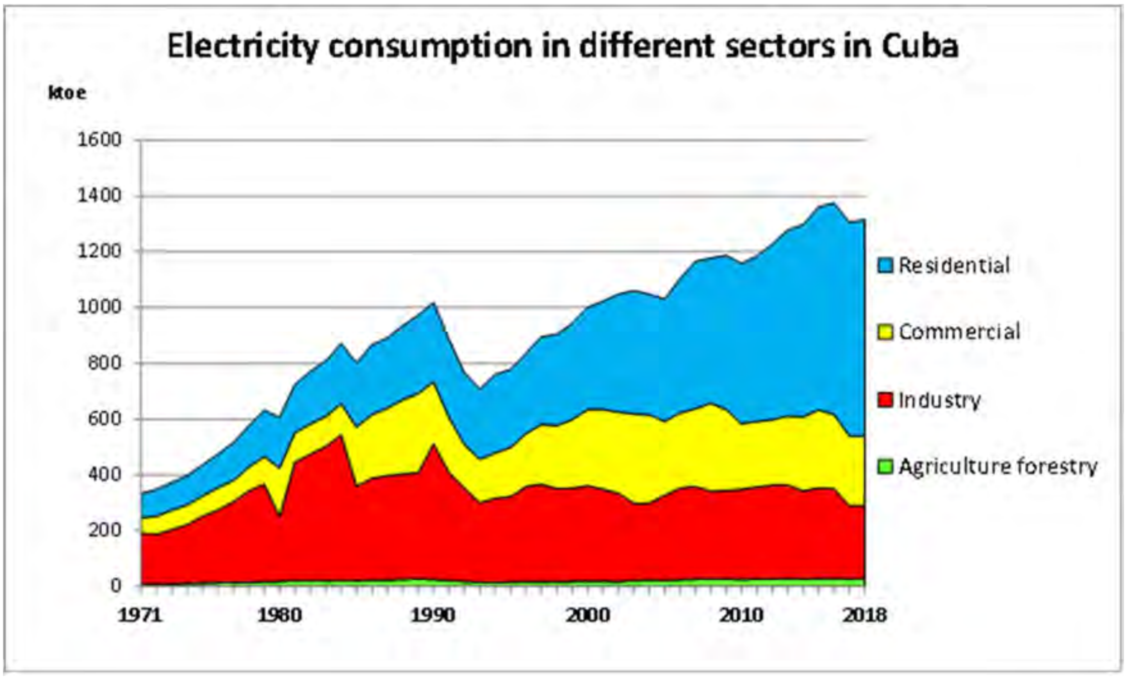


Figure 11. *Electricity consumption in Cuba. Data source* (IEA, 2020)

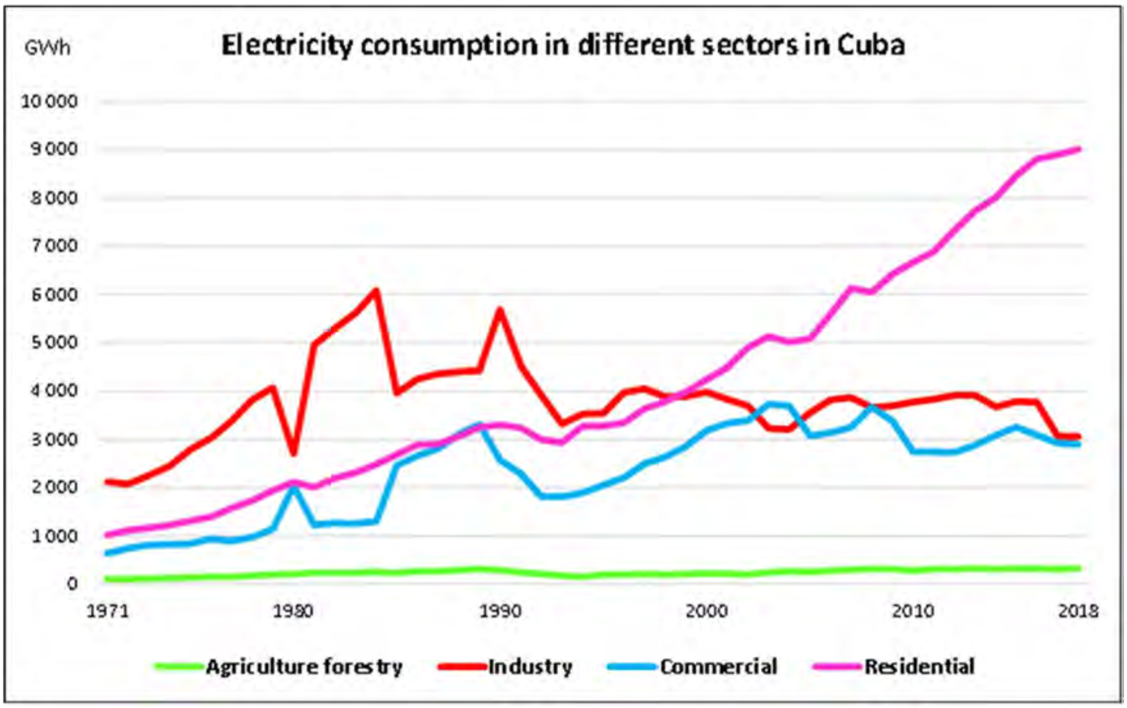


Figure 12. *Electricity consumption in different sectors in Cuba. Data source* (IEA, 2020)

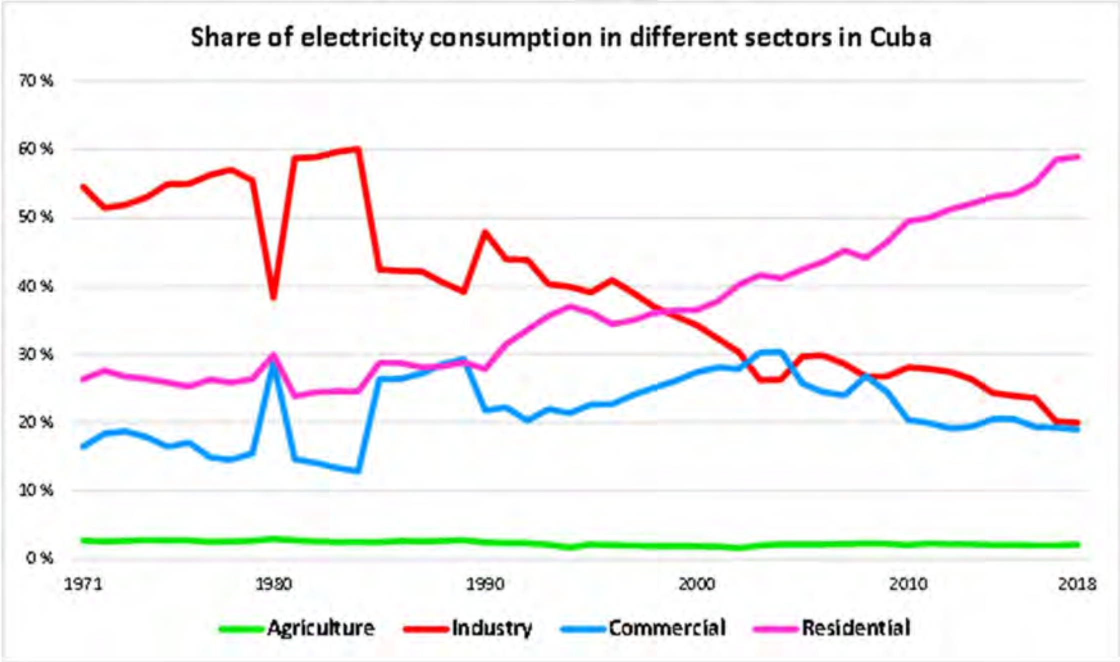


Figure 13. *Share of electricity consumption in different sectors in Cuba. Data source* (IEA, 2020)

The electricity intensity in Cuba, which in this case, means the amount of electricity consumed per million USD of value-added, increased until 2000 but has decreased after that (See Figure 14). This is an indication of the structural shift in the economy. Transition to a less energy-intensive service economy has been the factor behind this development.

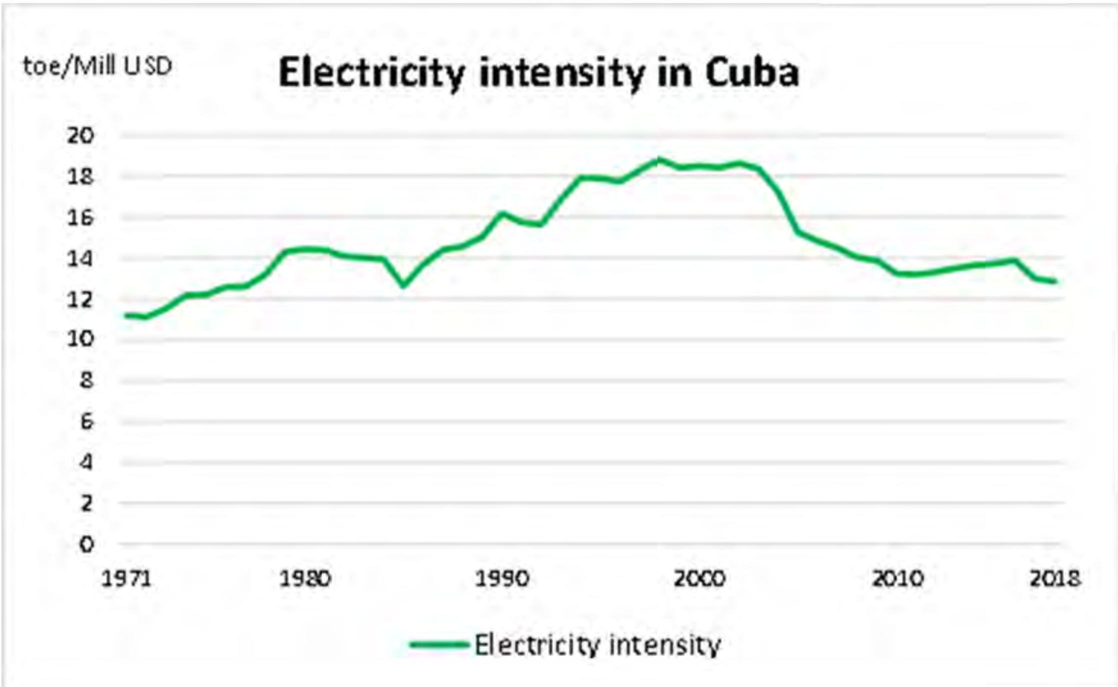


Figure 14. *Electricity intensity in Cuba measured as energy use (toe) per GDP (Mill USD). Data sources* (IEA, 2020; UNStats, 2021).

The sectoral electricity intensities are illustrated in Figure 15. Here we can see that both the industrial sector and the service sector have been able to improve their energy efficiency after 2000. The transition to a larger share of the service sector in the total GDP formation has made it possible to further improve the energy efficiency of the economy.

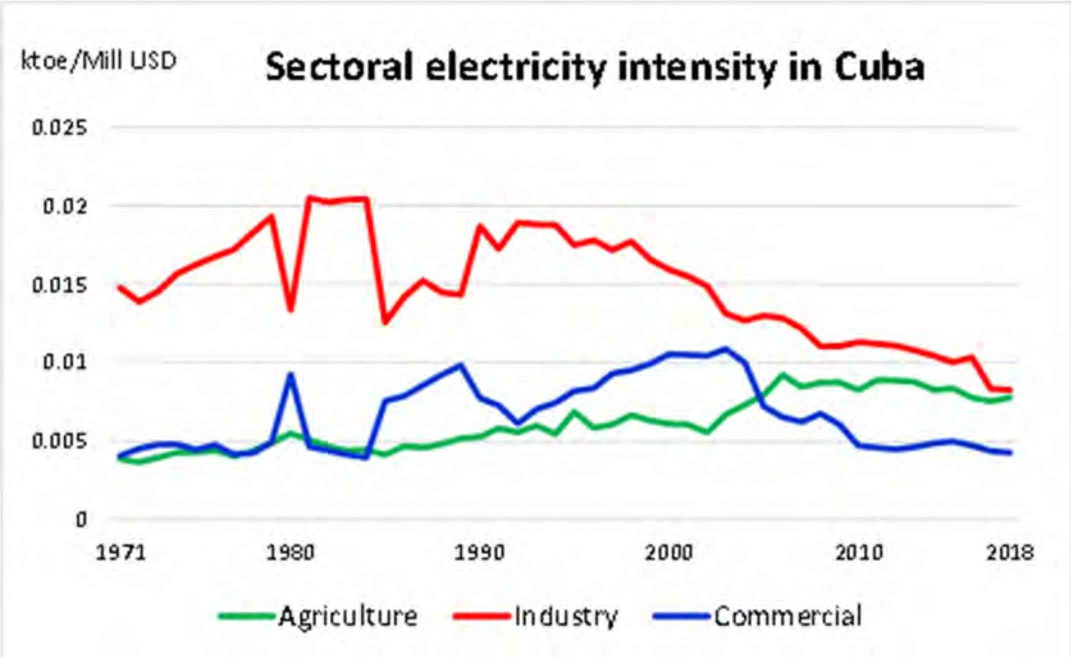


Figure 15. *Electricity intensity in different economic sectors in Cuba, measured as energy use (ktoe) per value added (Mill USD). Data sources (IEA, 2020; UNStats, 2021)*

The final energy consumption in different sectors in Cuba is illustrated in Figure 16. The industrial sector still dominates the energy consumption with its large fuel consumption even though its energy consumption has decreased.

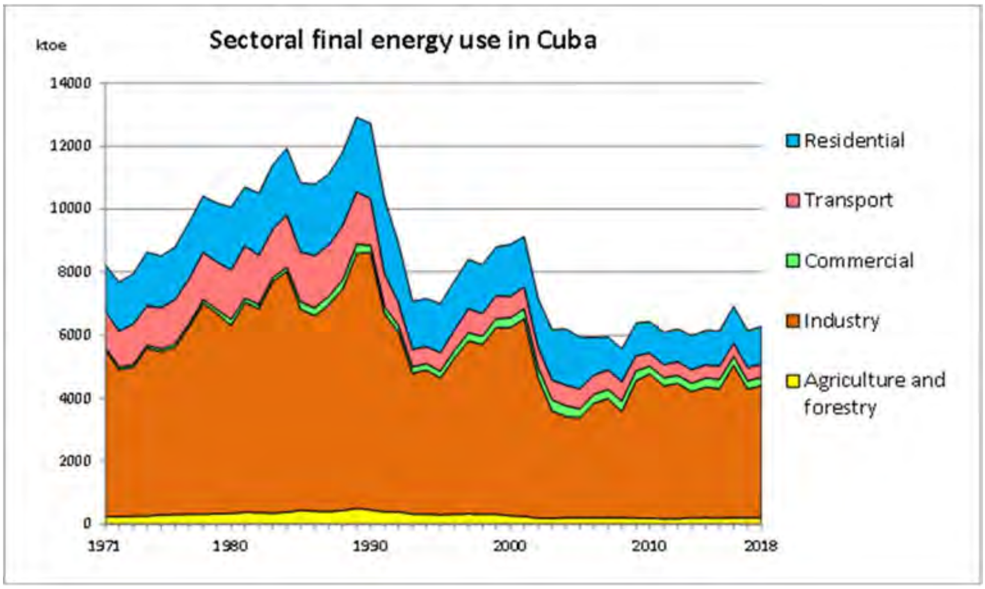


Figure 16. *Sectoral final energy use in Cuba. Data source (IEA, 2020).*

The fuel use in Cuba is illustrated in Figure 17.

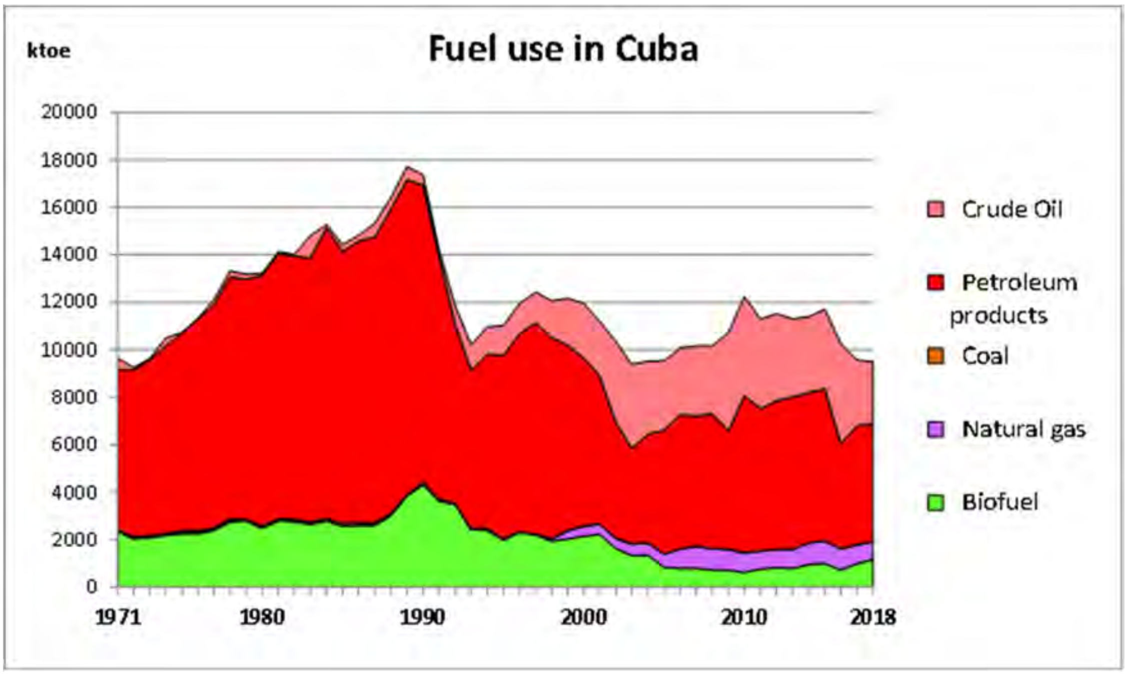


Figure 17. *Fuel use in Cuba. Data source* (IEA, 2020).

The industrial energy use is shown in Figure 18. The decrease in bagasse use (biomass) can clearly be seen in the figure after the collapse of the Soviet Union and the subsequent reduction in sugar export and production. The shift from petroleum product consumption to a larger share of crude oil consumption is indicative of the availability of fuels and the price differences.

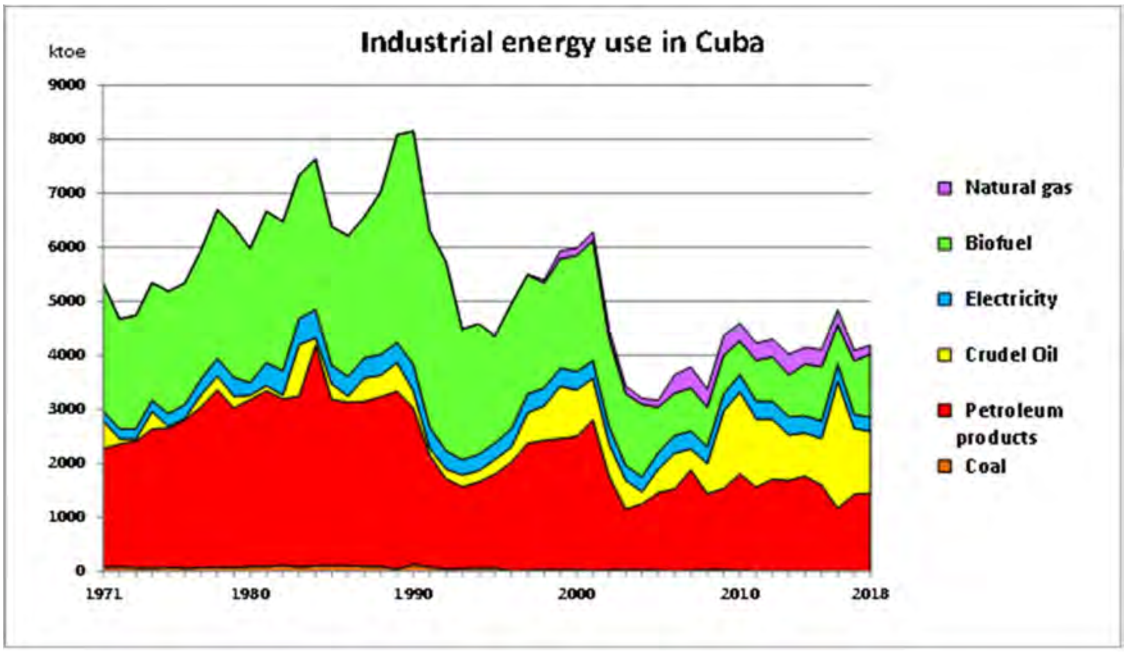


Figure 18. *Industrial energy use in Cuba. data source (IEA, 2020).*

Residential energy use in Cuba is shown in Figure 19. The earlier dependence on biofuels (firewood, charcoal) has reduced considerably and the use of electricity has grown fast. The use of petroleum products decreased as a result of the energy revolution (started in 2006) when a lot of kerosene-based cooking was transformed into electricity. Part of the residential energy use during the last years could be attributed to the service sector. The electricity use in the 'casa particular' type accommodation by tourists is in the statistics allocated to residential consumption even though it is part of the service sector.

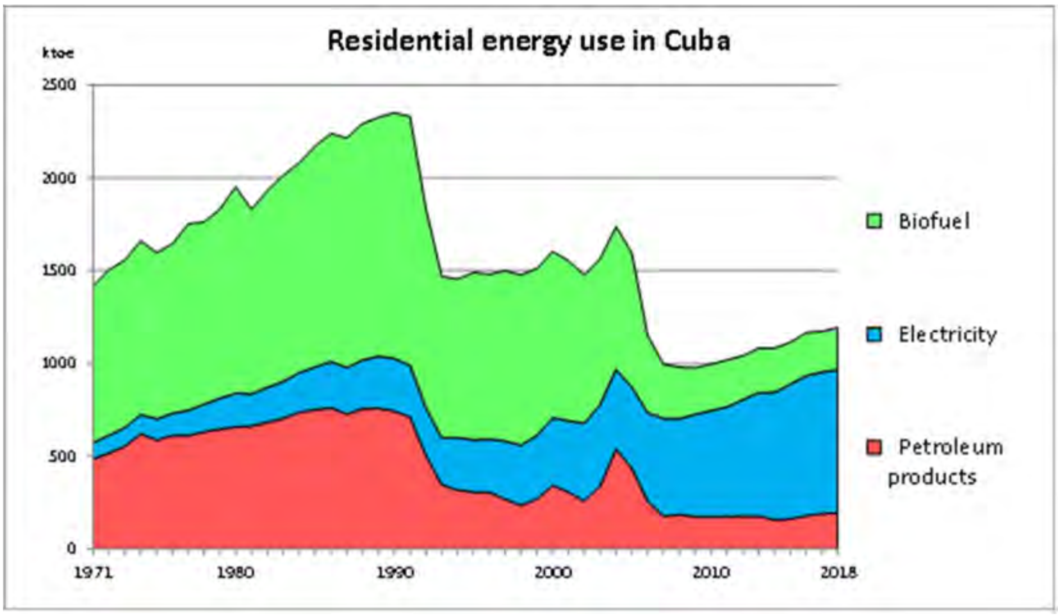


Figure 19. *Residential energy use in Cuba. Data source (IEA, 2020).*

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II.3. PhD Research work

II.3.1. System for knowledge management and innovation of territorial governments, focusing on energy economics for sustainable local development

Anaely Saunders Vázquez, Miriam Lourdes Filgueiras Sainz de Rozas and Jyrki Luukkanen

Abstract

Cuban municipalities are in the process of changing after the approval of the new Constitution, which grants them autonomy and the possibility of managing their resources integrally.

However, several obstacles make municipal management difficult, such as the limited capacity of governments to plan, regulate, control, and supervise activities and processes, the insufficient use of municipal planning, and the lack of tools and skills for energy management.

Based on these limitations, the objective and the scientific novelty of the research focus on the development of a system for the management of knowledge and innovation of territorial governments with a focus on the energy economy for sustainable local development (SKIMEn), as well as the design and implementation of an integrated energy management and planning model, contextualized to national conditions, both as support for decision-making.

Keywords: knowledge management; innovation; energy management and planning; local development.

Introduction

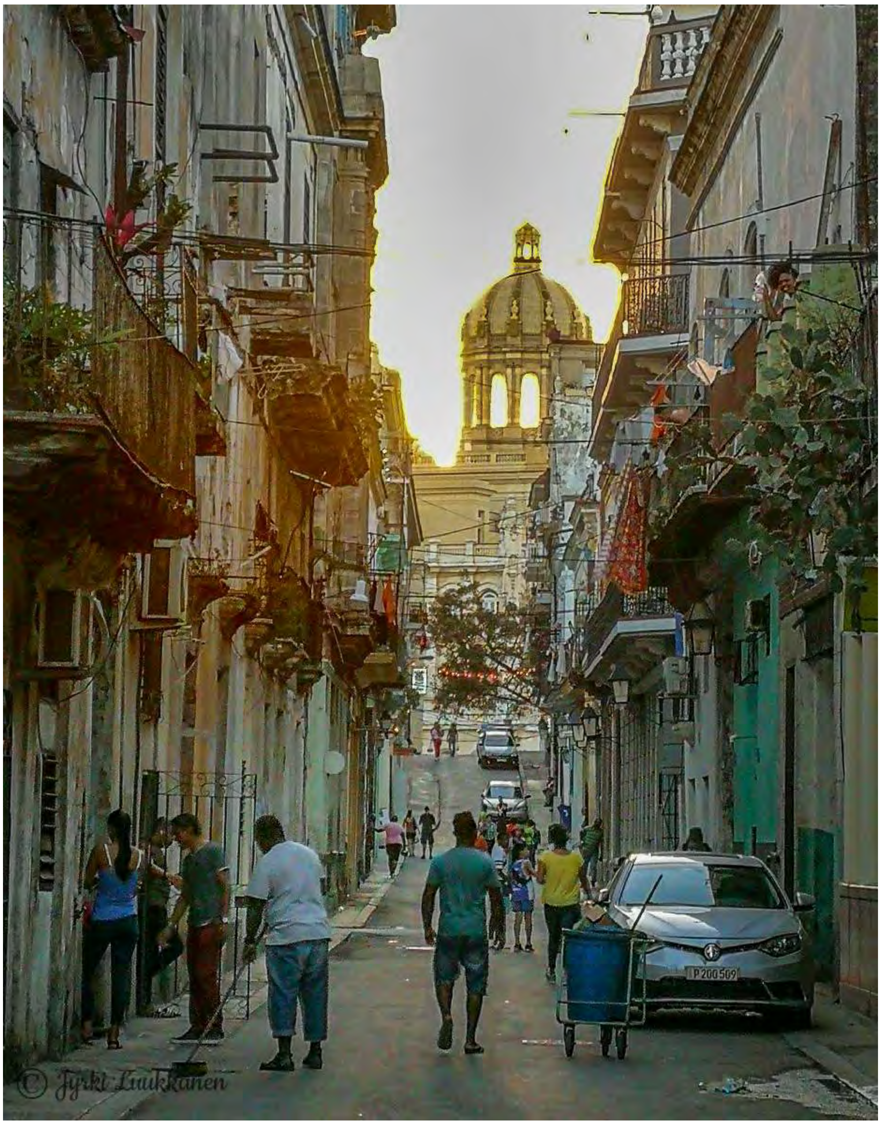
In the process of approval and implementation of the Guidelines for the economic and social policy of the Party and the Revolution (PCC, 2017), priorities were established for the development of the country, being the local sphere where these materialize, by turning the municipality into the fundamental space for the development of its endogenous potentialities (Guzón Camporredondo and Hernández Márquez, 2015). A paradigm shift in municipal management in the short and medium-term must occur after the approval of the new Constitution of the Republic of Cuba in 2019 (ANPP, 2019:69–113). In this new stage, the law grants autonomy to the municipality, which allows the management of the territory's resources in an integrated manner (ANPP, 2019:104). In this way, the municipality becomes the primary political-administrative unit of Cuban society with legal personality and to satisfy local needs (ANPP, 2019:104).

These normative changes must become promoters of modifying the forms of territorial action in terms of structure, direction, control actions, planning, and the execution and development of strategies in the short, medium, and long term.

The Constitution grants the municipality several prerogatives (ANPP, 2019:108–9) , among which are:

- approval and control of the economic plan, the municipal budget, and the comprehensive development plan;
- control of all institutions, local and national, established in each territory; financial, productive and service, healthcare, preventive and social, scientific, educational, cultural, recreational, sports, and environmental protection activities in the municipality.

These modifications allow the introduction of changes in municipal strategies, materialized in policies, and regulatory and normative references. By transforming direction management models, there are new opportunities with more decentralized planning and governance methods by transforming management models of the directorate. Decentralized governance will change the role of political, economic, and social actors in the territory with more participatory management.



Museum of the Revolution, Havana

These transformations imply that the local development envisioned is based on a conception of a sustainable, integral, and viable process, creator, articulator of actors and subjects, innovative from all points of view, but where planning plays a fundamental role (Guzón Camporredondo and Hernández Márquez, 2015).

System Proposal for the management of knowledge and innovation in territorial governments with a focus on the energy economy for sustainable local development (SKIMEn)

To carry out any analysis at the territorial level, it is vital to achieving the articulation of the essential processes of the territory, valuing the municipality as an organizational network, which will allow: expanding the knowledge base and its capacities; share costs and resources; become a flexible organization that must adapt to changing and challenging environments, and develop new strategies and synergies, taking into account current circumstances (Henao Castrillón and Zapata Giraldo, 2018). In this context, as a cross-cutting element, energy impacts each of the development activities, plans, and strategies, not only work as a resource but also by valuing the growth in demand, energy savings, and efficient use.

In this scenario, territorial governments face several challenges related to the energy issue. Therefore, within their Local Development Strategy, governments must consider the impact of energy development and evaluate different elements:

- the influence of autonomy in territorial energy management and the training of its specialists and officials in this area;
- the administration and/or creation of new institutions, industries, services, enterprises, based on the use of endogenous energy resources (fuel, electricity, gas, etc.), considering that these resources are allocated centrally by the national level;
- the creation of structural, human, and financial capacities, so that the municipality/territory functions as a microgrid that articulates all sectors and processes as a circular economy;
- the social, cultural, and technological impact of the implementation in the territory of the National Plan for the introduction and use of renewable energy sources, as well as its regulatory framework (Ministerio de Justicia, 2019);
- the growth of electricity demand in the territory due to measures that increase the quality of life of the population (Figueredo Reinaldo et al., 2019);
- the implementation of municipal energy management models and their impact on the environment;
- diversification of the territorial energy mix, with an effect on infrastructure changes and the high costs of its transformation;
- establishment in municipalities or territories of mechanisms for the export and storage of energy;
- capacity building for local energy planning.

For this reason, the research considers that local governments must incorporate the essential concepts of the energy economy into their territorial management model (Bouille, 2004) and manage elements such as energy efficiency, smart grids, energy planning, energy demand, distributed generation, the energy mix, among others.

Therefore, there is a need to design and implement a comprehensive municipal energy management and planning model that is adapted to national conditions, with a local vision of energy development linked to technological change. Unfortunately, this topic has been studied in recent years in a fragmented manner (Correa Soto et al., 2018). The research proposal is to integrally assess this issue based on knowledge management and innovation's contribution with this background. There are several conceptions about these issues, but authors such as Soto and Barrios (2006) consider knowledge management as a set of processes and tools that allow the systemic integration of actions to use and use knowledge, information, and accumulated experience. In the qualitative development of an organization or organizational network. Knowledge management is an integrative process where information management, technology management, and human resource management converge. In the case of innovation, it is an informational process in which knowledge is identified, acquired, processed, and transferred. Managing technological innovation requires the organization to change continually.

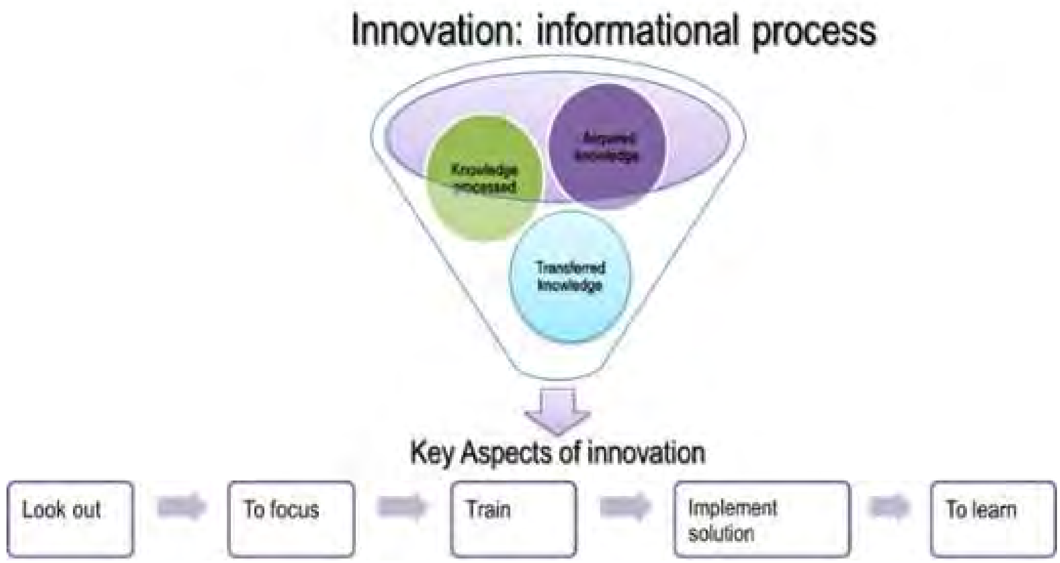


Figure 1: *Innovation as an informational process (Saunders Vázquez, 2012)*

Based on the analysis of the conditions of Cuban municipalities, the current research has assessed what scholars of territorial issues such as Guzón Camporredondo and Hernández Márquez (2015) and Correa Soto et al. (2018) have identified as obstacles that limit the management of municipal development. Among them are:

- The limited capacity of municipal governments to plan, regulate, control, and supervise activities and processes.

- Lack of institutional capacities, management, integration mechanisms, and strategic vision in municipal governments, where operations and a focus prioritize working in the short term characterize their management.
- The insufficient articulation of municipal planning tools and the absence of a local-territorial perspective.
- Lack of tools and skills for energy management and an institutional mechanism.
- There is no synergy between national programs, projects, and actions promoted from other levels and local development strategies.
- The imperfect definition of indicators to measure and evaluate processes

In conclusion, territorial governments lack tools for the theoretical and practical implementation of local energy development, to improve its management, the achievement of vital territorial objectives, and the formulation of Municipal Development Strategies by not incorporating the energy dimension and its impact on different aspects: political, economic, social, technological, environmental and cultural.

Formulation of the Scientific Problem: The territorial development management model does not guarantee the systemic integration of the energy dimension and sustainable local energy development in the formulation of Municipal Development Strategies, which does not favour the use of its potentialities and endogenous resources. The purpose of the research is to overcome the shortcomings that limit the territorial development model, incorporating the energy dimension as a transversal axis that influences each of the processes and systems by promoting synergy between the potentialities that each territory has as a space strategic and self-managed.

The field of research is Sustainable Local Energy Development.

The research **hypothesis**: it is possible to contribute to the improvement of the territorial development model by integrating the energy dimension through the development of knowledge and innovation management system of the territorial governments with an energy-economy approach for sustainable local development, as support decision-making, territorial autonomy and the formulation of Municipal Development Strategies.

Definition of objectives

The study's general objective is to develop a knowledge and innovation management system for territorial governments, focusing on the energy economy for sustainable local development (SKIMEn) to improve the sustainable local development management model applied in various country municipalities.

As specific objectives this research proposes:

1. Build the theoretical - conceptual framework of research from different approaches and adjusted to current trends, which contributes to improving the management of sustainable

local development by incorporating local energy self-sufficiency, renewable energy sources, and energy efficiency.
2. Design and implement a comprehensive energy management and planning model (EnMPM), its procedure, and the integration, adaptation, and implementation of different tools of international practice adjusted to the reality of Cuban territories.
3. Analyze the impact of different indicators of sustainable energy development in achieving the critical objectives of municipal development strategies using the Sustainability Window (SuWi) tool (Luukkanen et al., 2019).
4. Apply the SKIMEn and EnMPM to test the general hypothesis of the research in the territories under study.

The research topic is valued in an integral and multidimensional way to achieve the expected results from knowledge management and innovation vision.

Theoretical and methodological approach to the research

The academic and conceptual spectrum addressed in the study focuses on Management and Innovation as strategic processes and how they act at the territorial level. The research is holistic, given the very nature of the object of study and the need to shape the proposal from various elements, models, and methods developed in different countries and published in contemporary literature.

Different techniques to get the results:

- Interviews with officials and cadres of the municipal government;
- Creation of a focus group with the main actors and interested persons to evaluate a cross-impact matrix with essential elements that influence each territory;
- Survey on territorial energy demand validated in four municipalities selected for economic, social, structural, and cultural conditions.

In addition, the government's innovation-oriented management model for Cuba (MGGI) (Díaz-Canel Bermúdez and Delgado Fernández, 2021) will be taken into account, and it will be analyzed how the SKIMEn is articulated in this model when applied locally. The design of the SKIMEn will incorporate the vision, transversality, and interdependence of the elements contained in the Sustainable Development Goals (SDG), promoted by the United Nations (UN/CEPAL, 2018), which includes a specific one on affordable energy and clean. The research applies the sustainability window approach (SuWi), a tool for evaluating sustainable development in its three dimensions: social, environmental, and economic (Saunders and Luukkanen, 2021). This analysis, novel for the conditions in Cuba, is aimed at making visible the changes necessary to carry out at the local level to achieve a more sustainable state, analyzing the impact of the SDG indicators on the rest, to turn them into drivers of sustainable local development.

The research will also take into account the strategic axes, design under a systemic approach, described in PNDES 2030 (Ministerio de Economía y Planificación, 2020), which articulate the proposal for economic and social development and create, from its area of influence to the achievement of that long-term purpose. The study evaluates other analysis criteria, such as replaceable amounts of fossil energy; avoidable emissions of CO_2, NOX, and SO_2; cost minimization; as well as universal access to energy in isolated rural communities. Tools such as LINDA and FlexTool adapted to the country's conditions support territorial energy analysis and modeling and energy planning scenarios.

Research novelty

The scientific novelty of the research focuses on the development of the system for the management of knowledge and innovation of territorial governments with a focus on the energy economy for sustainable local development (SKIMEn), as well as the design and implementation of comprehensive model management and energy planning (EnMPM), contextualized to national conditions as support for decision-making.

The social, economic, and environmental importance of research

The SKIMEn can contribute to improving territorial capacities and addressing problems in the energy field, using multi-criteria analysis in the elaboration of its municipal development strategies, with energy management and planning tools, which include, among others: technology, innovation, technology transfer, circular economy, and project management.

It contributes to the training of community actors in energy issues to promote synergies between local potentialities. The SKIMEn must lay the methodological bases so that each territory has an energy management and planning model, which will improve the sustainable territorial development management model. The development and application of an integrated model of territorial energy management and planning (EnMPM) and its procedure will improve the preparation of Local Development Strategies and the achievement of the objectives of the territories by including the energy dimension in said strategies. The SKIMEn in the future will affect the substitution of imports, as well as energy saving and efficiency, and the change of the energy matrix. Not only will the change happen at territorial but also at the national level and on local energy sustainability.

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II. 3.2. Short-term net-load forecasting method for distribution power systems with utility-scale PV

Saddid Lamar Carbonell, Eduardo Sierra Gil, Rafael Trujillo Codorniu and Luis Vázquez Seisdedos

Abstract

The importance of energy demand management has been more vital in recent decades as the resources are decreasing, the emissions are getting higher, and the use of renewable energy is increasing. Recently, short- term net-load forecasting has played an important role in energy supply-demand management for the efficient use of energy. It becomes a challenge when there is a high penetration of renewable sources into the electric grid because of their variability. This research aims to develop a short-term net-load forecasting method/methodology for distribution power systems with large-scale deployment of grid-connected solar photovoltaics.

Introduction

Renewable energy sources help meet the growing energy needs of countries and, at the same time, help to reduce dependence on foreign countries and reduce greenhouse gas emissions (Yesilbudak, Colak, and Bayindir, 2018). Solar energy is one of the most promising energy sources since it is clean, abundant, and freely available. In addition, the cost of photovoltaic (PV) modules has had a significant decrease in the last years (SolarPower Europe, 2018). For these reasons, it is one of the most popular renewable resources and keeps increasing its share in electric power generation globally.

In Cuba, the government has encouraged the increase of participation of renewable energy sources in the energy matrix of the country since 2014. Nowadays, various programs of renewable energy generation are carried out in the country, like wind, biomass, and solar generation, but up to now, the last one has shown better results. Currently the generation from fossil fuels predominates to supply the country's demand. Among renewable sources, photovoltaic solar energy is the second largest participation in the national electricity matrix with a generation of 13.2 ktoe in 2019 (ONEI, 2020).

Since 2014, the Cuban government is developing a solar PV program to install 700 MW of capacity in the whole island by 2030, as the initial plan. But at the beginning of 2021, this program was updated to increase its plan to more than 2000 MW the participation of solar energy in the power system (Extremera San Martín, 2021). So far, in Cuba, 227 MW have been installed in photovoltaic systems connected to the electrical system, of which 215 MW in 72 parks (utility scale) synchronized with the Electric System (ES) and 12 MW installed on roofs and areas belonging to the entities. The installed power in the parks directly connected to the ES allows covering 6.72% of the electricity demand during the noon hours (Alonso Falcón, Figueredo Reinaldo, and Sifonte Díaz, 2021).

The utility-scale PV systems directly inject all the energy into the main grid. In Cuba, those are usually connected at the distribution power grid, close to the consumers, allowing to supply the demand with a minimum of losses and negative effects to the environment. Generally, they have capacities between 1MW – 6MW that, in many cases, represent near of 50% of the demand in the distribution grid. However, this PV penetration has some negative impacts on the grid. In van der Meer, Munkhammar, and Widén (2018), the authors state that the penetration is a direct function of variability into the grid. This is due to the stochastic nature of PV generation depending on weather conditions, given by solar irradiation, cloudiness, atmospheric temperature, dew point, among others (Ahmed et al., 2020).

The impact on the grid of a utility-scale PV system is high because of the large number of interconnected panels close to each other. So, the clouds can reduce the production of several panels at once, leading to a significant decrease in the power delivered to the grid by the PV plant in a short time. For operating feeders, with a utility-scale PV system, the variability in solar power production propagates into the net load profile and reduces the accuracy of net load forecasts at the distribution feeder (Kaur, Pedro, and Coimbra, 2013; van der Meer et al., 2018). That situation is also a concern in Cuba, where PV power forecast errors as high as 13% have been reported.

An accurate short-term load forecast (STLF) is a cost-efficient solution to issues mentioned later. Also, STLF impacts positively the operation, scheduling, and stability of the power system. Because of that, this research is focusing on methods and methodologies of short-term net load forecasting for a distribution power grid with high solar penetration (more than 35% of the demand), suitable for the Cuban study case. The STLF has a prediction horizon from one to three days. It helps power system operators with various decision-making in the power system, including supply planning, generation reserve, system security, dispatching scheduling, demand-side management, and financial planning. A large number of methods for short-term forecasting of load and renewable generation have been proposed, which can be generally categorized into conventional models and artificial intelligence (AI) -based models.

The conventional methods are the time-series models, regression models, and gray models (Wei et al., 2019). They use historical data (time series) and regression-based approaches to predict the demand. These models do not need a lot of historical data and can construct the explicit relationship between energy consumption and its influencing factors, such as lagged observation, temperature, gross domestic product (GDP), and population (Deb et al., 2017). However, they are capable of yielding better results while solving linear problems.

In contrast with conventional models, AI-based forecasting models do not rely on the explicit relationship between energy consumption and its influencing factors but learn from a large amount of historical data for prediction instead. These models, such as artificial neural network (ANN) and support vector regression (SVR), have a strong capability in dealing with nonlinear problems and are thus widely used in energy consumption forecasting, particularly in short-term forecasting (Wei et al., 2019), but they require a huge among of data. Newly developed data-driven techniques, such as clustering (Wang et al. 2015), spare representation and deep learning techniques (Mocanu et al., 2016) have been used for feature extraction and regression analysis (Wang et al., 2018).

A general diagram of the distributed power system can be observed in Figure 1. Where the net load (L_n), can be calculated as $L_n(t) = L(t) - L_{PV}(t)$, where L is the actual load of the grid and L_{PV} represents the solar power generation onsite the grid, as it's referred in Kaur et al. (2013) and Wang et al. (2018).

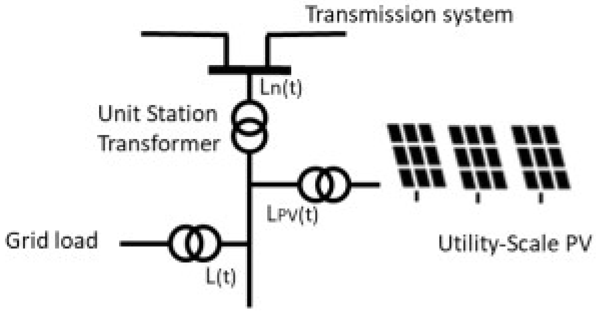


Figure 1. *Distributed power system with utility-scale PV.*

In recent years, the interest for studying and forecasting the net load has increased due to renewable penetration into the distribution power grid. Nevertheless, most of this studies are focuses in load demand and solar generation forecasting separately. The net-load forecasting studies can be classified as direct and indirect according to the calculation strategy. In the direct strategy, the time series of the net-load is the only series to be forecasted. While, in the indirect strategy, at first, the time series of renewable energy sources generation and load demand are individually forecasted through the models and then, based on the outputs of the models, the net-load forecasting is performed (Alipour et al., 2020).

Several works regarding direct net load forecasting have been developed (Alipour et al., 2020; Haben et al., 2021). One of the first works was presented in Kaur et al. (2013), where it is used persistence model, autoregressive models (AR and ARMA) and k Nearest Neighbors (kNN) model to forecast in horizons of 15-min and 1-hour for two cases: (1) high solar penetration and (2) no penetration. One of the main conclusions in this work is that the uncertain of the PV power the main cause of the load forecasting error. A hybrid approach of actual demand short term forecasting is presented in Yu, Mirowski, and Ho (2017). The used data was from operational grid feeders (4) and they were implemented for 10-, 20-, and 30-min forecast horizons. Authors employed two models: Artificial Neural Network (ANN) and Support Vector Machine (SVM), which were enhanced using three methods: time series detrending, daytime/nighttime model training, and using sky image features as exogenous inputs to the stochastic models; where the most successful method was the detrending. The results showed the increasing of the forecast error as the PV penetration gets high levels. In Sepasi et al. (2017)is proposed a very short-term load forecast framework to optimize the performance of grid-scale battery energy storage system. The load forecast framework consists in two parallel – series methods. The parallel section of the forecasting is based on the CVNN method considering the similar day approach. The series sections are based on the CVNN and spline techniques.

Others authors have investigated the indirect net-load forecasting strategy (Alipour et al., 2020). Considering that the electricity demand characteristic is almost independent from solar power generation, as demand is affected mostly by the socio-economic and human factors while solar power generation is related to weather conditions, forecast of the net demand becomes cumbersome as the PV systems populate. In order to forecast the net demand, the actual demand and solar power generation should be forecasted separately. In this sense, Kaur, Nonnenmacher, and Coimbra (2016) presented a comparative analysis of two different net load forecast approaches: additive and integrated. In the first one, solar and load are forecasting individually and subtracting to obtain the net load forecast. While in the second, the solar power forecast was used as an input into the net load forecast model. The authors found that the integrated approach outperforms the additive based on its accurate results. In addition, no exogenous input was used to predict solar power in this work. The proposed approach takes changing atmospheric clearness, panel soiling and efficiency degradation of PV panels into account using adaptive clear sky model and heuristics.

Some researchers consider that deterministic, or point forecasts, do not express uncertainty into the grid with high renewable energy penetration, which is important for stakeholders. In that sense, probabilistic forecasting has gained more attention in the last years, as it is possible appreciate in recent works (Hong and Fan, 2016; van der Meer, Munkhammar, et al., 2018; van der Meer, Widén, and Munkhammar, 2018; Wang et al., 2018). The advantage of probabilistic forecasting is that the level of uncertainty can be expressed that accompanies the prediction by means of a probability density function (PDF) or prediction interval (PI), which enables stakeholders to make better informed decisions (van der Meer, Munkhammar, et al., 2018).

These works above mentioned were developed for PV penetration behind-the-meter or small-scale PV systems. However, no work was finding where is consider high penetration based on utility systems, with PV generation about 35-55% of the demand into the distributed power system. That is why the following is proposed as research problem:

Research problem

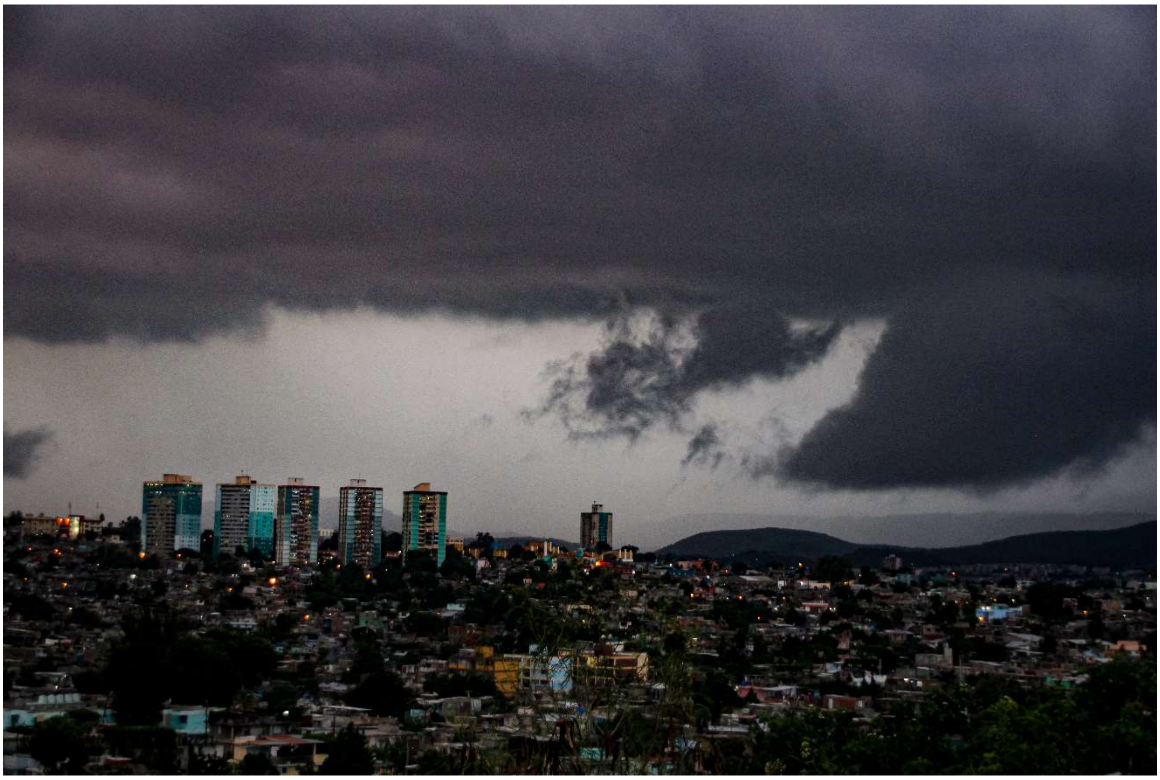
The research problem examines the difficulties in the operation of the energy distribution system with solar penetration due to low accuracy of the short-term net load forecasting when the photovoltaic generation represents 40 ± 5% of the system demand.

Research purpose

This research aims to develop a short-term net load forecasting method/methodology such that it accomplishes the following requirements:

- It should be suitable for distributed power systems with high penetration of renewable energy in the form of large-scale deployment of grid-connected solar photovoltaics.

- This model should be capable of adjusting itself taking into account information from the PV plant (efficiency and capacity), and weather variables (temperature and solar irradiance).



Storm approaching Santiago de Cuba

Novelty

There are several works about short–term forecasting of the load and solar generation. But they are mainly applied at the micro-grid or household level. Most of the studies are focused on geographically distributed PV systems rather than on a single point. Therefore, the scientific novelty of this research is to propose an auto-tuning short-term net load forecasting method/methodology specific for distributed power systems with utility-scale PV systems, taking into account PV plant real-time information and weather variables.

Importance: social, economic, environmental

Energy problems are vital for the security and well-being of societies. According to economic theories, energy is one of the most important resources for industrial production, and forecasting energy consumption is an important phase for macro-planning of the industry and energy sectors (Ghalehkhondabi et al., 2017).

Short term net-load forecasting plays a key role in the formulation of economic, reliable, and secure operating strategies for the power system to make the balance between the supply and demand of the energy. Forecasting errors lead to an unbalanced supply-demand, which negatively affects the operational cost, network safety, and the service quality of the supply network (de Felice, Alessandri, and Ruti, 2013).

Underestimation of energy consumption can lead to a power outage, which can be harmful both for the economy and the daily life of society. On the other hand, the overestimation of energy demand may lead to creating unused capacity that is equal to wasting the resources, which harms the financial and environmental factors. The latter is another important aspect of energy consumption forecasting because using fossil fuels is the most common way to produce electricity and make greenhouse gasses as a result of burning these fuels. Therefore, using models to accurately forecast future energy consumption trends is an important issue for the power production and distribution systems.

Currently in Cuba, approximately 95 % of electric energy production is based on fossil fuels and the other 5% comes from renewable sources. Nevertheless, the Cuban government has encouraged an increase in the use of renewable energy generation since 2014. Under this scenario, the proposal of this work (short-term load forecasting model/methodology) brings the benefits of keeping the electric service quality in the distribution power system with high solar energy penetration and contributing to efficient energy use with less CO2 emission.

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II. 3.3. Optimal expansion planning of distribution network with high penetration of distributed energy resources

Irina Salazar Fonseca, Sami Repo and Thomas Stetz

Abstract

Due to climate change and environmental concerns related to greenhouse gas emissions by fossil-fuel-based power plants, the integration of renewable Distributed Energy Resources (DER) into Distribution Networks (DNs) has significantly increased in the last decade on a global scale. Despite the benefits offered by renewable distributed generation technologies, several economic and technical challenges can result from an inappropriate integration of distributed generation in existing DNs. Therefore, optimal DNs expansion and reinforcement planning considering high penetration of DER are of paramount importance to ensure that the performance of DNs can meet the expected power quality, power loss reduction, reliability, and profitability. A mathematical model for stochastic planning of the optimal expansion of DNs including renewable distributed generation and smart grid technologies will be developed in this research. This study focuses on the multi-objective optimization methods where reliability, grid losses, investment costs, and uncertainties are considered.

Introduction

All over the world, electricity is traditionally supplied by a centralized power generation system that usually consists of a few large-scale generation units and an extensive interconnected network that transmits and distributes electricity to a range of domestic, commercial, and industrial consumers (Ehsan and Yang, 2018). In a centralized power generation system, the generation units generally have large capacities, several hundreds of megawatts, and the power flow is unidirectional. On the other hand, a distributed power generation system consists of small-scale generation units, renewable and no-renewable, as shown in Figure. 1, directly connected to the distribution networks (DNs), with capacities ranging from a few kilowatts to several megawatts. In this context, DNs are in the transition phase from passive to active networks resulting in bidirectional power flows (Abapour, Zare, and Mohammadi-Ivatloo, 2015). At the same time, the bulk integration of renewable distributed generation technologies has started to affect the secure and reliable operation of DNs (Usman et al., 2018). Since distribution networks have high R/X ratio, the intermittent nature of renewable distributed generation technologies causes a large variation in their operating conditions. Several technical issues such as voltage rise, reverse power flow, unintentional islanding, voltage unbalance etc. have been reported in the published literature as a consequence of the presence of these technologies in DNs (Karimi et al., 2016). This rapid integration of renewable distributed generation technologies has brought about a paradigm shift in the way conventionally passive distribution networks have been planned and operated.

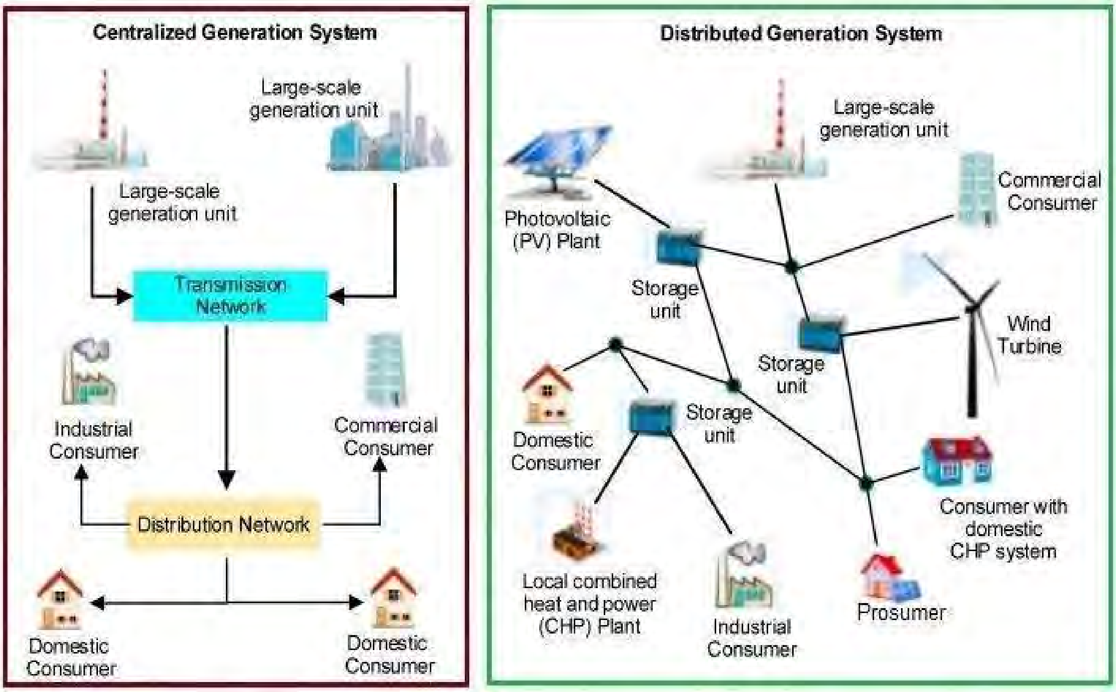

Figure 1. *Centralized and distributed power generation system (adapted from Ehsan & Yang, 2018).*

Conventionally, the distribution network planning (DNP) approaches have mainly focused on figuring out the optimal siting and sizing of various system elements (i.e. substations, feeders, transformers, circuit breakers and capacitors) to meet the load growth, in addition to ensuring the security and reliability of the power supply operation (Ehsan and Yang, 2019). Typically, the DNP has aimed at minimizing the investment costs, the operational and maintenance costs, and the power losses and for the solution of the conventional DNP problem a specified load demand forecast is assumed over the planning horizon, where the distributed generator (DG) units are naively modelled as negative loads. However, the conventional approaches used in DNP are not capable to give an adequate planning solution for the active distribution networks. Instead, this research will look for active distribution networks planning (ADNP) models that effectively consider the impact of the uncertainties and challenges of the optimal integration of distributed energy resources (DERs).

The intermittent generation of the non-dispatchable renewable DGs imposes operational uncertainties on the power availability. Numerous other factors including load variability, demand growth and electricity market prices introduce further operational uncertainties to the ADNP. Therefore, the ADNP models incorporate several emerging concepts, such as generation and load forecasting, multi-criteria network planning, and advanced control and power management (Ehsan and Yang, 2019). The robustness and reliability of the ADNP-based solutions significantly depend on the adequate characterization of uncertainties. These uncertain parameters can be classified into technical and economic uncertain parameters, as summarized in Figure. 2.

Figure 2. *Uncertain parameters associated with the ADNP.*

The general framework of the ADNP models can be categorized into three phases: the modelling, the strategy and the optimization (Ehsan and Yang, 2019).

1. **Modelling phase:** focusses on the modelling of the distribution system, the dispatchable and non-dispatchable generators, the storage units, the plugged-in electric vehicles (PEVs) and the other system components, e.g., controllers, sensors, and inverters.
2. **Strategy phase:** the comprehensive strategy of the planning problem is formulated, such as the planning type, the timescale, the planning decisions, the optimization objectives, and the mathematical formulation.
3. **Optimization phase:** the optimization algorithms and tools are employed to achieve the optimal ADNP solution.

The planning type can be the construction of a new distribution network or the expansion/reinforcement of an existing distribution network. In this research, the main focus will be on the expansion/reinforcement of substations, feeders, and distributed generation to meet the continuously increasing load demand and the integration of distributed energy resources in an existing distribution network.

Different approaches have been developed for the active distribution networks expansion planning (ADNEP) under new conditions to mitigate the undesirable impacts of the inappropriate integration of distributed generation into existing DNs, Table 1 presents a unifying taxonomy of the reviewed ADNEP models. It can be observed from Table 1 that multi-objective approaches and stochastic programming call for further research effort.

Table 1. Taxonomy of the reviewed distribution expansion planning models

Reference	Stages	Objective function	Mathematical formulation	Optimisation algorithms
(Haffner et al. 2008)	Multi-Stage	Min Costs (investment + operation)	MILP	Branch-and-bound algorithm
(Popović and Popović 2010)	Multi-Stage	Min Costs (investment + losses + interruptions)	DP	-
(Soroudi and Ehsan 2010)	Single-Stage	Min total costs and technical dissatisfaction **[Multi-objective]**	DP	Hybrid multi-objective Immune Genetic Algorithm and Fuzzy technique
(Falaghi et al. 2011)	Multi-Stage	Min Costs (investment + operation + reliability)	pseudo- DP and OPF	Genetic Algorithms
(Borges and Martins 2012)	Multi-Stage	Min Costs (energy loss + non-distributed energy + investment + energy imported from transmission)	pseudo- DP	Genetic Algorithms
(Aghaei et al. 2014)	Multi-Stage	Min Costs (investment + operation), energy not distributed and Active power losses and voltage stability index **[Multi-objective]**		Modified Particle Swarm Optimization
(Bagheri, Monsef, and Lesani 2015)	Single-Stage	Min total costs	DP and OPF	Improved Genetic Algorithm
(Santos, Abaide, and Sperandio 2015)	Single-Stage	Min Costs (Distribution Network Expansion + Transmission Network Use of System Charges)	Mixed-Integer NLP	Greedy Randomized Adaptive Search Procedure
(Munoz-Delgado, Contreras, and Arroyo 2016)	Multi-Stage	Min Costs (amortized investment + maintenance + production + energy losses + unserved energy)	MILP and stochastic programming	
(Mohtashami, Pudjianto, and Strbac 2017)	Multi-Stage	Min Costs (capital + operational)	mixed-integer NLP and OPF	Optimization software FICO Xpress
(Mokryani et al. 2017)	Multi-Stage	Maximize the social welfare	OPF	-
(Gouin, Alvarez Herault, and Raison 2018)	Two-stage	Minimise Capital EXPenditure	Linear programming and PT	-
(Moradijoz, Parsa Moghaddam, and Haghifam 2018)	Two-stage	Minimise Net Present Value	MILP	Immune-Genetic Algorithm
(Rastgou, Moshtagh, and Bahramara 2018)	Single-Stage	Minimise total social cost	mixed-integer NLP, non-convex DP, and PT	Improved harmony search algorithm
(Ugranli 2018)	Multi-Stage	Min Costs (Investment + electricity purchased	MILP	-

		from the grid + unserved energy)		
(Xie et al. 2018)	Multi-Stage	Min total present cost and closeness of spanning tree **[Multi-objective]**	mixed-integer NLP and stochastic optimisation	-
Reference	**Stages**	**Objective function**	**Mathematical formulation**	**Optimisation algorithms**
(Arasteh et al. 2019)	Single-Stage	Minimize the planning costs and the Expected energy not supplied Maximize investment, Operation and maintenance costs **[Multi-objective]**	mixed-integer NLP	Multiobjective particle swarm optimization
(Canizes et al. 2019)	two-stage	Min total expected planning cost	MILP, stochastic optimisation and DC-OPF	-
(Muñoz-Delgado, Contreras, and Arroyo 2019)	Multi-Stage	Maximize the profit of the distribution company and owner of distributed generation units Minimize operation cost **[Multi-objective]**	mixed-integer trilevel programming	Benders decomposition
(Pinto, Unsihuay-Vila, and Fernandes 2019)	Multi-Stage	Min total cost of the expansion planning and system average interruption duration index (SAIDI)	mixed-integer NLP and stochastic optimisation and OPF	non-dominated sorting genetic algorithm II
(Wang et al. 2020)	Single-Stage	minimize the total annual investment cost, energy loss, and shared electric vehicle waiting cost	mixed-integer, non-convex optimization problem	Natural Aggregation Algorithm

MILP: mixed-integer linear programming
DP: dynamic programming
OPF: Optimal Power Flow
NLP: non-linear programming
PT: probabilistic techniques

Research problem and question

Several innovative developments in power distribution systems have taken place around the world. One of them is related to the minimization of the carbon footprint using a large-scale integration of renewable energy sources (RES) such as wind and solar. Due to this, the European Union (EU) has set the target of achieving 20% of RES in the final energy consumption by 2020. Furthermore, to meet the energy requirements beyond 2020, a new agreement in the EU aims at a target of 27% of RES penetration by 2030 (Mokryani et al., 2017) On the other hand, Cuba aims at a target of 24% of RES penetration by 2030 (Arrastía-Avila and Glidden, 2017). Similar goals are plans in Cuba and the EU this would lead to DNs with large DER penetration and new opportunities to reconsider how the service agreement to end customers is fulfilled. Meeting an appropriate integration of DER into existing DNs will require a transformation in the planning methods, tools, and management of the DNs.

The research will investigate the following research question in order to achieve its objective:

<u>How the distribution networks expansion planning should be done to ensure the optimal integration of distributed energy resources into existing distribution networks?</u>

Distribution network installations, Havana

Novelty

The development of a simple enough stochastic dynamic DN expansion planning model, which may consider the uncertainty of load and production, consider multi-objective (e.g., grid capacity and reliability) investment problem and integrate a variety of smart components, control methods and novel flexibility solutions, to be utilized in real-life DNs. The novel formulation of the ADNEP problem is one key research question in the thesis.

Practical results are in addition to case studies knowledge and simplified expansion planning solution, which might be implemented as a part of DN's information systems for long-term grid planning including the impacts of renewable distributed generation and the benefits of smart grid technologies and services.

Importance: social, economic, and environmental

With the penetration of DER the DNs will face a revolution in the coming decades and therefore the need for a new DN planning framework is essential for the development of the entire energy system. On a social, economic and environmental scale, the developed methodologies and framework enables cheaper integration of renewable energy sources and electric vehicles into electricity system by planning smarter DNs. Reliable DNs with the presence of DER ensure possibilities for an improved health system (without blackouts in hospitals) in the well-being of the home (refrigerators to preserve food, cooking with electricity, etc.), in the educational system (use of educational facilities based on electricity) and in reducing greenhouse gas emissions.

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III. Electricity grid development

III. Introduction

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The Cuban power system has evolved and developed differently than most power systems for economic, political, and technical reasons. The nation had had limited access to electricity before 1959. Its development has leaned towards a centralized generation but emphasizes getting electricity to all corners of the island from 1960 to 2000. Cuba went through severe problems in 2005 due to the difficult economic situation and the blockade imposed by the United States. Because of it, the country has introduced solutions addressed to reduce electricity consumption and moved towards distributed generation. Currently and in the future, the nation aims to introduce renewable energy sources to achieve energy independence that allows the country to generate electricity at the lowest cost and the energy quality required by consumers. Thus, the current chapter of this book begins with the history, evolution, and future trends of the Cuban power system. From the system's point of view, these challenges have two essential aspects, closely related to each other: how to carry out the system's operation and how to introduce renewable sources in a way that does not affect the operation and stability of the power system. The main aspects are briefly exposed and then linked to the Cuban problem and the characteristics of its power system. However, the research considers international experiences, how the Cuban power system operates, how that operation would be with an increase in renewable sources up to 24%, and what aspects should be taken into account. These aspects should be carried out so that the integration of renewable does not cause significant changes in the system and possible stability problems and takes into account the standards for connecting renewable sources to the grid.

From the perspective of helping to decide and assess how to face the problem of the integration of renewable sources in Cuba, the universities and the research that can be done plays a fundamental role in the future of Cuba. These research projects are done as a part of the doctoral programs of each university and in cooperation with the Cuban Electric Company (UNE) to help the decision-makers.

This chapter shows some of the studies being carried out in close connection with problems the country faces related to integrating renewable sources. These studies have the help of the European community, in this case, the Government of Finland, and are part of an international project entitled Cuban energy transformation: Integration of intermittent renewable sources in the power system (IRIS).

This chapter includes the analysis from the global point of view and the impact of the system with renewable sources studied by Orlando Delgado Fernández. He develops a model to analyze small signal stability for a weak power system with high renewable resource penetration, having the Cuban power system as a basis for the study. The world and Cuba are moving towards a future with renewable sources where electric cars, smart grids and microgrids play an important role in

the development of renewable sources. Raynel Díaz Santos is developing a bi-directional multilevel converter for the vehicles connected to grid applications as part of the project.
Moises Ferrer Vallin carries out a work that serves as a compliment by aiming to develop a method to obtain adequate wind power according to its control to reduce the frequency deviation in isolated electrical systems with high wind power penetration. This study will also be applied to the Cuban power system.
The integration of renewable sources is a global problem and a local one. In Cuba, the decision has been to connect photovoltaic solar energy in the distribution networks in small plants up to 10 MW distributed throughout the country. The second one is the evaluation and fault detection in grid-connected photovoltaic systems by analytical methods developed by Roger Proenza Yero. Finally, Frank Grau develops control strategies with power quality indicator criteria for investors in grid-connected micro-systems.
More studies are being carried out in other universities of the country. This is just a tiny sample of the work being developed in some of the Cuban universities that cooperate with universities from other countries. The objective is to announce our work and obtain feedback from the international scientific community. This is a humble contribution to world scientific development and the development and sustainability of the Cuban power system.

Electricity network sub-station, Havana

III.2. History and future development needs of the Cuban grid

Miguel Castro Fernández and Miriam Vilaragut Llanes

A brief and historical recount of Cuban grid development.

Before 1959 the existing policies in the Cuban electricity sector could be characterized by limited access to the electricity service by society, with a very low level of internal solutions (Reseach + Development + Innovation). Cuba was only an importer of equipment and technologies in the electricity sector. (Altshuler and González, 2010).

In 1844 the first electrical industry was inaugurated (Altshuler and González, 2010) with the multiplication of lighting installations in cities throughout the island, electric power installations in some industries such as sugar factories, cement and beer, the development of the electric tramway the electrification of the country is accelerated. By 1957 the Cuban Electric Company had an electric power generation capacity of 361.6 MW, of which 214 MW were installed in the metropolitan area of the Cuban capital (see Figure 1).

Figure 1. *Generation capacity of the Cuban Electricity Company in 1957* (Altshuler and González, 2010).

In 1960 the Cuban government decreed the nationalization of the Cuban Electricity Company. A new stage in the development of the Cuban electricity sector started. In 1973, the first 220 kV transmission system lines were energized. With this, the current National Electric Energy System (NEES) was inaugurated. It was designed to interconnect all the important electrical plants in the country. For 2004, the installed capacity reached 4048 MW (see Figure 2).

Figure 2. *Installed capacity in the NEES for 2004 (UNE, 2004).*

Technologies

In summary, at the time of the triumph of the Revolution, Cuba had a total capacity of 397.1 MW, most of which was generated by thermal power stations. It divided into three subsystems: the Western one, the largest in terms of extension and capacity, extended from Pinar del Río to Nuevitas; the Northern one, which, leaving Nuevitas, included the electrical installations of the current provinces of Las Tunas and Holguín, and part of Camagüey; and the Southern one, which included the electrical installations of the current provinces of Granma, Santiago de Cuba and Guantánamo. On the other hand, some towns and cities throughout the country were fed by small diesel plants that operated out of sync with the other plants (Llamo Hernández, 1985).

In January 1959, a process of transformation of the electrical system began. Throughout this period and until 2004, new investments in a generation were based, fundamentally, on thermal units of 100 and 169 MW, plus one of 320 MW that came into operation in 1984. In 2004, the capacity of the Cuban NEES was 4048 MW, and only 1.58% and 10.12% corresponded to Distributed Generation (DG) and Gas Technology, respectively. Most of this was provided by the thermal power stations (CTE), which have been operating for an average of 25 years, with 60% availability, frequent breakdowns and high consumption.

At the end of 2004, the country's electrification rate reached 98%. The Cuban grid operated 3 112 km of lines and 23 electric substations of 220 kV as well as 4 387 km of lines and 11 substations of 110 kV conforming to the NEES transmission system. The electric distribution subsystem is conformed by 10 130 km of lines and 2 133 substations of 33 kV joint 39 464 km and 45 4440 km of primary/secondary circuits respectively. In addition, there was a high percentage of losses in the electricity transmission and distribution networks due to their characteristics.

External factors such as the tightening of the economic blockade against Cuba by the USA, the limited access to international markets, the abrupt cut-off of oil supplies and their high prices, the impossibility of carrying out maintenance and repairs to the power stations and distribution networks and the scourge of frequent hurricanes, caused the collapse of the NEES in 2004.

During 2004 and 2005, the Government reformulated its strategies, with an integrative and systemic approach. Starting in 2005, the ENERGY REVOLUTION IN CUBA was developed, which contemplated the simultaneous development of more than 20 programmes aimed at rational energy use. The concept of distributed generation (DG) was introduced as a way to increase the reliability of the NEES. Two hundred new generation nodes were installed, which brought about a radical change in the typology of the electrical system (see Figure 3). The need to diversify the sources of generation also began to be assessed.

Figure 3. *Distributed generation (DG) power plants in the Cuban NEES* (Castro Fernández et.al, 2018b)

In 2010, studies began to introduce renewable energy sources (RES) into the Cuban NEES. Thematic working groups on wind and photovoltaic energy were created. In 2012, Presidential Decree No. 3 of 11 December 2012 (REVE, 2014) was issued, which provided for the creation of a Government Commission for the elaboration of the policy for the prospective development of RESs in the period from 2014 to 2030. In June 2014, the Council of Ministers approved the Policy and the schedule for the implementation of RESs in the Cuban NEES. In 2015, the Foreign Investment Opportunities Portfolio for RESs in Cuba was created and the regulatory framework began to be drawn up, which was finally approved in 2019 and made public through Decree Law No. 345 (Ministerio de Justicia, 2019).

As a background of electricity generation facilities to this program, we can point out the presence of a total of 470 MW installed in the sugar industry, for self-supply and delivery of energy to the NEES, but with low-efficiency technology. This only allowed to obtain about 37.6 kWh/ton of processed cane. In addition, there were 64 MW installed capacity in about 140 mini and small hydropower plants. To this background, different actions were carried out in the 1999-2005 period such as

1. Installation, in 1999, of an experimental park on Turiguanó Island with ECOTECNIA technology and a capacity of 500 kW.

2. Installation of small wind, photovoltaic and hybrid systems in more than 400 Family Doctor's offices located in mountains and remote rural areas, mountain hospitals, more than 2300 schools, more than 1800 TV rooms, as well as social circles and border facilities.

Subsequently, in the period 2005-2010, another group of actions associated with the use of these technologies at the national level in Cuba were carried out, which can be summarized as follows:

a. Installation of 3 experimental wind farms, with a total capacity of 11.25 MW, with VERGNET, GAMESA and GOLDWING technologies, from France, Spain and China respectively.
b. Prospecting and characterization of the Cuban wind potential, with a network of 88 automatic wind parameter measurement stations at heights of up to 50 m in 32 areas of the country, and a network of 12 reference meteorological stations, with measurements up to 100 m high.
c. Preparation of a National Wind Map with an estimate of technical potential exceeding 1100 MW, considering the use of 1.5 MW wind turbines, backed by the guarantee of the International Consultancy Garrad Hassan & Partners (Garrad Hassan Iberica branch)

Local electricity grid, Santiago de Cuba

Present situation

The schedule for the implementation of MEFs in the Cuban SEN established, from the beginning, the following objectives are the following:

1. To install 2144 MW of electrical power from:

    a. 19 Bioelectric plants, with a total of 755 MW associated.
    b. 13 wind farms (PE), with a total of 633 MW associated.
    c. More than 100 photovoltaic solar parks (PSFV), with a total of 700 MW associated.
    d. 74 small hydropower plants, with a total of 56 MW associated.

2. Exploiting other potentialities from the use of solar thermal energy, forest biomass, as well as municipal solid waste, industrial organic and agricultural waste to generate electricity

3. To achieve with this investment to generate more than 7 245 GWh per year with these technologies, which would represent around 24% of the total energy generation, allowing an approximate disbursement of 3 700 million for imports and to stop emitting to the atmosphere more than 6 million tons/year of CO_2.

At the end of 2019, the situation regarding the introduction of RESs in Cuba presented the following panorama:

a. 4 wind farms with a total of 11.8 MW installed.
b. 67 solar photovoltaic parks, with a total of 156.4 MW installed.
c. 147 small and mini-hydro plants, with a total of 64 MW installed.
d. 57 sugar plants (AZCUBA), with a total of 470 MW installed.

The contribution of RESs, within the Cuban NEES generation mix, was 818 GWh in 2019, which represented 4% of the total (20167 GWh/year), including own consumption by the sugar plants; of the facilities connected directly to the network and served by the Electricity Corporation. In 2019, 124.0 GWh were generated with hydropower, 11.0 GWh with wind energy and 240.0 GWh with photovoltaic solar energy for a total of 375 GWh.

The Cuban NEES maintains the predominance of electricity generation with fossil fuel, and there is also a programmed investment of 4 blocks of 200 MW each, which is supposed to start its execution in 2020. 560 MW of combined cycle from the existence of plants that have units of liquefied natural gas for later will also be executed.

From the point of view of improvements to the NEES, the work during 2019 was done on the generation scheme and the capital repair of important blocks of two thermal power plants. Six new photovoltaic solar plants (PVSPs) with a total power of 14.8 MWp were synchronized to the NEES. Some sections of transmission lines were completed (including the output substation of the Ciro Redondo biomass plant, to be synchronized in 2020). Other works were carried out at the distribution level, the latter with the aim of strengthening the electricity network.

The system is operated according to a procedure that is governed by technical requirements, established on the basis of existing experience, which must be replaced by a network code. The Cuban network code still has some limitations, and it will be modified as long as it defines how the NEES is to operate depending on its immediate, medium and future needs.

Future development needs concerning the development of renewable energy sources

A study released in April 2020 (Ram et al., 2020), presents three transition paths in the energy sector, with different scenarios. The "leadership" scenario foresees 100% renewable energy as early as 2040. The "moderate" scenario would reach the goal in 2050. The "laggard" scenario means reaching 62% with RES in the European system by 2050.

The reported international trends (DNV-GL, 2019), in terms of electrical power systems and energy consumption, are moving towards:

- An impact of energy efficiency in all sectors of the economy and its decoupling with the increase in population and GDP, in view of the expected peaks in primary energy supply in 2030 and in final energy consumption in 2033, in the latter case supported by the electrification of different sectors of the economy.
- Reduction of investment costs in the use of solar photovoltaic (SPV) and wind energy (WE), which would lead to a significant increase in the use of both RESs.
- Electric vehicles (EV) will represent 70% of passenger transport in 2050, 50% of commercial transport, and almost 100% of transport with two and three-wheelers.

Under these tendencies, it can be understood that an electric power system (EPS) with high integration of RES would operate in a somewhat different way than what is known today. According to Henbest (2020), the main characteristics of a EPS under these conditions would be:

- Large fossil fuel plants would no longer operate 24 hours a day with high capacity factors.
- RES would become part of the backbone of the system, with this configuration characterized by large amounts of SPVs during the day and WE during the night.
- The batteries would support the variable RESs, having a high use value under the concept of charging when RESs are abundant and prices are low, and discharging during the hours of high demand, high prices and when the presence of RESs is lower.
- Under this operating scheme, the cutting of variable MEFs, when they have an overproduction, is a feature, not an error.

Distribution grid transformers, Santiago de Cuba

The Cuban NEES is an isolated system, so when planning its expansion and maintenance, as well as its daily operation, it should be done under this concept. The interconnected national grid does not have the possibility of obtaining energy from any other source, other than its own. For this reason, the network's operating needs, technical requirements and current and future investments must be in line with this fundamental characteristic and take into account the climatic characteristics that prevail in Cuban territory.

The change in the energy mix in Cuba, and in particular the electricity production mix, with the introduction of RES in the Cuban NEES, requires the correct absorption of these technologies. Generation schemes must be designed and implemented in accordance with the reality of the national territory, as well as changes in the topology and operation of the network, both immediately and in the medium term, and in the future.

As an example in Cuba of applying these conditions to the selection, location and sizing of PVPs, one can cite the decision to build the parks at a distance of more than 8 km and with a capacity of no more than 5 MW. This has meant that normal cloudiness events occurring in the national territory do not significantly affect the MW generated by this technology. Furthermore, the average variability of this technology due to cloudiness in the Cuban SEN is reduced.

In this same direction and in an immediate way, for example, it should be taken into account that even though Cuba presents a solar radiation potential of 5 kWh/m^2/day approximately, there are other climatic and environmental factors that influence the efficiency of use of photovoltaic panels. High temperatures almost all year round, dust content in the air and cloudiness are among the most important factors. The high relative humidity should also be considered, which has more limited

negative effects but can penetrate through the panel frames reducing their energy production (Castro Fernández et.al, 2018a).
The issue of variability (and randomness) of the energy produced by solar photovoltaic and wind power plants is another element to be considered. Many countries take into account the support that the purchase of energy from other sources, including renewables, represents for bordering countries. Another variant is the inclusion of energy storage systems, which still have a high cost on the market. Some countries have opted for over-sizing generation schemes, beyond the capacity of investors to deliver to the grid, this variant being less costly.
These factors should be included in the designs of the distributed generation schemes of which RESs are a part in Cuba. For example, a SPV field with an oversizing of 30% in its photovoltaic generator, above the capacity of the inverter, would ensure the stability of the energy delivery expected by that field in the event of problems with increased temperature or humidity, excess dust, involvement of any panel in a chain, etc. This would be a solution almost negligible in cost, compared to that which would have an energy storage system that allows for similar results. The excess generation obtained under normal conditions can be delivered to areas with low storage capacity (at a lower cost) or simply cut the energy supplied by the park, which would be a normal event in its operation, as is proposed (Henbest, 2020).
Evaluations conducted using the "CubaLinda" model (Luukkanen, Akgün et al., 2015; Luukkanen, Panula-Ontto, et al., 2015) have made it possible to analyze the possibility of reaching a scenario with 100% renewable generation in Cuba. In this direction, a study carried out by Hohmeyer and Welle (2018) proposes that an adequate combination of wind, solar photovoltaic, biomass, hydraulic and pumped energy storage facilities, together with the use of biodiesel in the existing diesel generators in the country, as a backup to the grid, would cover the demand for electricity in Cuba for a consumption scenario of up to 60 TWh per year, as expected by the UNE for 2040 (Guerra Hernández, 2014). This includes electric mobility and the replacement of natural gas and oil in both the residential and industrial sectors.
In Vazquez et al. (2018) a more detailed analysis of the effects of the massive introduction of renewable generation in an electrical system is carried out. In a medium and immediate time scenario, new technologies will increase the control needs in an Electric Power System such as the Cuban NEES with a high penetration of renewable energy sources (in the order for 70 to go up to 100%, as indicated above), since a process would occur natural reduction of control in conventional thermal power plants, by reducing their role in the system. On the other hand, as synchronous generators are replaced by electronic power converters, the inertia of the system at the points of connection with the grid decreases and it becomes more sensitive to frequency variations. This effect will also be increased when electric drives based on energy-efficient converters are incorporated into the load. Similarly, the control of the voltage and safety of the electrical system, in the DG schemes, will differ from the control in the centralized scheme, as the current circulation will change depending on the state of the system, as discussed in Galván and et.al (2016).
These characteristics of a network with high RES penetration point to the need to change the way the network is operated and how its control is allocated, decided and executed. On the other hand,

in the Cuban NEES, the need to incorporate the concept of intelligent electrical networks (smart grid) will be imposed, in a relatively short time frame, which would allow the introduction of computer and communication technologies in the actions of control and operation of the electrical system. An example of this is the integration of technologies such as electric vehicles, which are emerging as demand-side storage systems to support frequency control. If it is decided to transform transport in Cuba to electrical technology, it would also be necessary to change the management of the Cuban NEES.

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III.3. Renewable power integration into power systems

Ariel Santos Fuentefría & Yrjö Majanne

Introduction

Each generation system containing integrated renewable sources has, to some extent, its own characteristics, functionality, and particularity. Some of them operate almost similarly compared to conventional generation-based systems, while others behave remarkably differently. It is important to identify and consider system structures appropriately so that the grid connection studies are as accurate as possible.

A power system needs to operate with high values of reliability and feasibility, supplying energy with the required quality of service all through the years. Conventional, deterministically operating generation plants, such as thermal and nuclear power plants, can be designed as a part of the power system with relative ease. However, including weather-dependent renewable generation sources as a part of the generation system, make the design of the power system more complicated.

Impacts of wind and solar energy connected in the power system are difficult to take into account in power system design, mainly due to the uncontrollable variation of their power production. For this reason, studies about the integration of wind and solar photovoltaic (PV) energy, known as variable renewable energies (VRE), in the power system, must answer several fundamental questions. How much wind or PV generation capacity can be installed in the power system while still maintaining the quality of service on the required level? Where to connect those VRE resources? What modifications and investments must be made in the grid to enable this connection? What are the costs and benefits of the project?

Technical requirements

There are relevant aspects for the connection of VRE generation in a power system, which will determine the type of feasibility study to be carried out. For example, the momentary production of wind and solar power can only be predicted within some interval of confidence. Therefore, it is necessary to have a mathematical model of the power system to simulate and analyze the impacts of the VRE generation on the operation of the system. Wind farms should be installed in locations where there are high wind speeds and sufficient consumption or existing power transmission capacity in the area. In those cases, the power grid must be restructured. Under Cuban conditions, solar, biomass, and mini-hydropower are connected in distribution networks, within the distributed generation concept, and it is important to analyze the impact of the connection at local distribution levels.

Grid code is a technical specification made by the responsible operator of the main grid. The grid code defines the requirements that a facility connected to a public electric grid has to meet to ensure a safe, secure, and economic operation of the electric power system. The grid code defines the procedures for grid operations and establishes the necessary requirements between the system operator and all users of the power system. The grid code specifies all the procedures relevant to the planning and operation of the grid, under both normal and exceptional circumstances.

The grid code is needed to harmonize the connection requirements of the renewable generation, based on power quality parameters and needs to maintain a stable operation of the system. Each country or power system has its own grid code, based on its own needs and characteristics. Some examples of grid codes can be found in Bruendlinger (2016); Luo et al. (2018); Tsili and Papathanassiou (2009).

The grid code defines issues such as voltage and frequency levels of operation, active and reactive power control, low voltage ride through (LVRT), high voltage ride through (HVRT), harmonics, flickers and rapid changes in voltage. The two most important parameters of the analysis are system voltages and frequency. The grid code defines how wind and solar PV power plants should react to disturbances in grid voltage and system frequency. LVRT and HVRT define how a generation unit should react to under- and overvoltage disturbances in the system. Especially a wind turbine rotor pitch angle control is vulnerable to voltage disturbances and may cause severe problems for an individual wind turbine as well as the whole power system in case of under- and overvoltage situations.

Cuba has a grid code based on the characteristics and particularities of its power system. The grid code is in continuous change to be adjusted and improved to obtain the best benefits from the increasing renewable generation. This ensures a greater utilization of VRE generation and ensures the stability of the grid with high shares of wind and PV generation in the system.

Figures 1 and 2 show aspects of the Cuban grid code related to voltage, and Figures 3 and 4 show those related to frequency. The renewable generating units must be able to absorb or inject reactive power as a function of the active power generated according to the active power – reactive power (PQ) curve in Figure 1. LVRT characteristic in figure 2 shows that renewable generation units must be kept connected to the grid during a voltage dip, where the voltage drops at minimum to 0.2 p.u. and rises up back to a value above 0.85 p.u. within 1 second after the disturbance occurred. This helps the power system to recover from quick and short-lived voltage disturbances in the system e.g. by preventing wind turbines from an automatic stop during this type of disturbance.

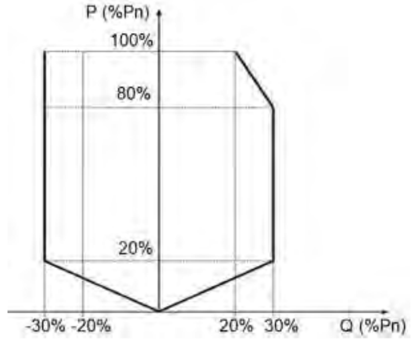

Figure 1. *Reactive power generation requirements in relation to active power according to the Cuban grid code.*

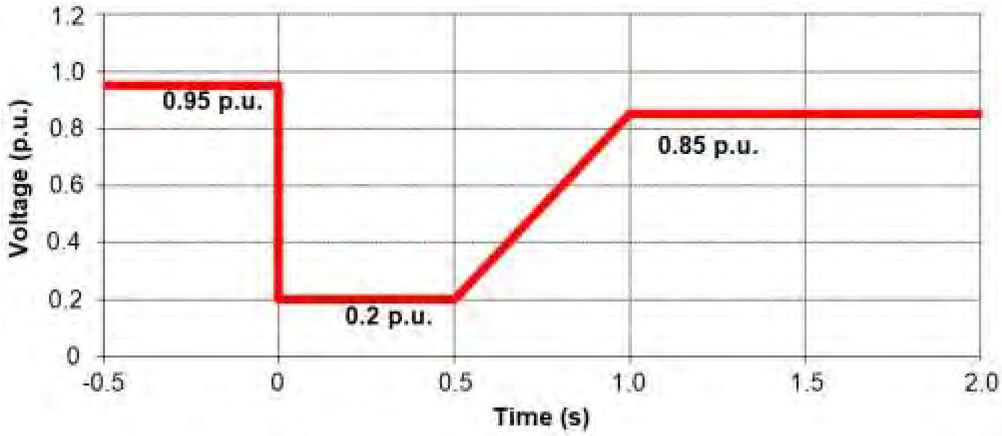

Figure 2. *Low voltage ride through (LVRT) requirements of the Cuban grid code.*

Renewable generation should be kept connected to the grid normally when operated in a frequency range between 58.5 and 61 Hz. Outside this frequency range, the renewable generation has the allowed disconnection times shown in figure 3. The active power controls of the generating units must meet the following requirements: normal allocated unit loads for frequencies between 57 and 62 Hz, changeable under load; and the response speed must be adjustable between 1 and 10% of the generating unit's rated power per minute. In case of an increase in frequency, the variable generation must be able to reduce its power output as a function of system frequency according to the ramp in Figure 4.

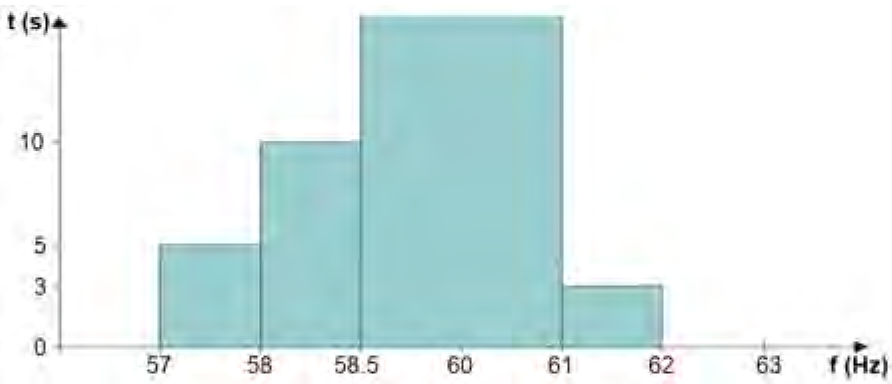

Figure 3. *Frequency limits and times for switching off the generators according to Cuban grid code.*

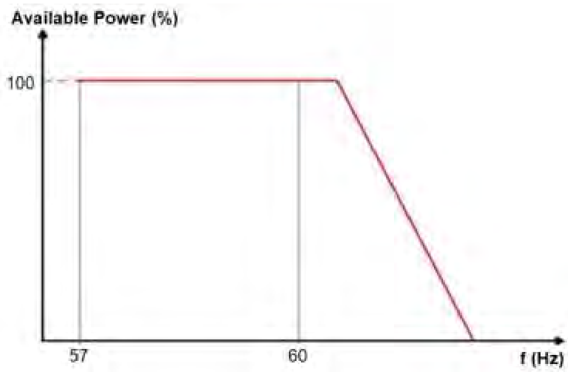

Figure 4. *Power - frequency response curve according to the Cuban grid code*

Studies related to Variable Renewable Energy integration

The studies about the integration of VRE generation into the grid do not have a fixed order, but they depend on the characteristics of each country or power system. However, it is necessary to cover them all to guarantee, as previously stated, the stability of the electric power system and the quality of service to all the consumers.

Feasibility studies of increased integration of VRE generation in the power system usually start with long-term studies, with a time horizon of more than 10 years. These analyses are performed based on the economic, social, and environmental goals, and technical features of the grid. The most common studies at this stage are:

- Studies about renewable energy resources in different locations. In these studies, the potential of wind or solar power generation in a certain area is analyzed by actual wind speed / solar radiation measurements, and a wind speed or solar radiation intensity map is prepared. This map allows the evaluation of how much energy could be generated and is it economically feasible to start the establishment of the wind or solar generation plant. Cuba has a wind map updated in 2018 developed by researchers from the National Institute of Meteorology (Alonso et al., 2019; Roque et al., 2017). The solar radiation intensity maps have also been established from different locations in Cuban.
- Scenario studies for energy planning. In these studies, impacts of different alternatives of VRE installations (capacity and location) and development of energy consumption, are studied. The applied scenario models characterize economic aspects such as growth in different production sectors, growth in demand, population growth, GDP, renewable potential studies and cost of electricity. The scenarios might be diverse and many alternatives can be analyzed, although all the scenarios must be reasonable and as close as possible to reality. Some studies about 24% penetration of renewable sources have been carried out by (Luukkanen et al., 2018 and Salazar et al. 2018). Also, a more ambitious study about a 100% renewable Cuba has been carried out by Hohmeyer and Welle (2018) and Luukkanen et al. (2022).
- The optimal scenario for increasing renewable generation. Resulting from the previous scenario studies the best scenario based on optimal investment and generation plan will be defined. This study allows having a more detailed plan and an annual program in order to achieve a given objective for any given year. Cuba's plan is to achieve 24% renewable penetration by 2030 (Vazquez et al., 2018).
- Modification of the existing power system. Based on the results from the previous analysis, an increased share of VRE generation in the power system will usually require modifications in the existing power system. As an example, if the share of VRE generation in the power system is increased, more flexibility in the power system will be needed as well. Increased flexibility can be achieved by increasing controllable power plant capacity with fast power response providing increased primary control capacity for frequency control, or by the installation of fast-responding energy storages, such as battery storages.

Another example about the analysis of the Cuban power system related to the installation of wind farms shows that the best wind resources are located in the northeast region of the country. However, the biggest power demand is in the western zone, which means that an analysis of transmission capacity between the eastern and western zone will be needed to assess the sufficiency of the transmission capacity. If there is not enough capacity, plans should be made to increase the links and strengthen the transmission capacity to avoid stability problems.

Transformer, Havana

Once a feasible scenario for power system development has been identified, the work shall continue on more detailed planning of the system in a shorter time horizon, usually a span between 5 to 10 years. These studies are known as medium-term planning studies:

- Scenario studies and optimal medium-term plan. These studies review and analyze scenarios based on the same parameters as in the long-term studies. The main difference is the time horizon. This study is to re-plan the connection of new renewable generation to the existing power system, having more precision in estimating the growth in the demand and market prices for projects with renewable sources.
- Flexibility studies. These studies analyze the properties of the modified power system needed to maintain the security of the service and economic feasibility taking into account the variability and uncertainty of demand and renewable generation at all time scales. From the point of view of frequency, the need to increase reserves in primary, secondary and tertiary controls is analyzed. From the point of view of voltage, the need to increase devices or elements for reactive power compensation is analyzed. Planning in a time span from 5

to 10 years, the acquisition of any necessary equipment to cover future needs due to the variable generation connection within the power system is decided.

- Planning of the electrical system. Similar to the long-term study and with many common points with the flexibility study, this study points out the reinforcements that must be made in the power system in terms of transmission lines, new substations, controllable generation/storage capacity, costs of expansion.

Finally, there are the short-term studies (within 5 years), which can be divided into local and system-wide studies. Local studies are carried out mainly to analyze the behaviour of the voltage levels in the nearby nodes due to the renewable connection:

- Determination of the connection point. In these studies, the main objective is to determine the best connection points of renewable generation to the grid. At the connection points and near buses, the behaviour of the voltage is analyzed, both under normal operating conditions and when a disturbance occurs. The goal is to ensure that the requirements of the grid code are met, and the system is capable to maintain stability. Other aspects that will be analyzed are power losses, line-specific power transfer needs, and possible changes in the configuration of the grid. In Cuba, for example, it was decided to connect PV plants in distribution networks with capacities up to 5 MW each. Due to this, it is important to analyze the behaviour of the distribution feeder and define the best connection point in each distribution network (Santos Fuentefria et all, 2019). More studies about the behaviour of the voltage and the influence of the renewable generation in the interconnection point in the Cuban power system are presented in Santos Fuentefria, Castro Fernández, and Martínez García (2012) and Santos Fuentefria, Martínez García, and Castro Fernández (2012).
- Calculation of the maximum connected renewable generation capacity. After defining the most suitable interconnection point, the maximum amount of tolerated VRE generation capacity is calculated. Integration of new VRE generation capacity in the existing power system should not jeopardize the stability of the grid, either under normal operating conditions or after the occurrence of a disturbance. The new VRE capacity also should not require significant reinforcements in the structure of the power system. If any aspect related to the power system structure is changed, e.g. grid reinforcement or installation of a new piece of equipment, the maximum allowable renewable generation capacity at the connection point should be calculated again. Due to this problematic feature of power system design, a new methodology for calculating the maximum power limit for wind power generation was developed and applied to the power system of Isla de la Juventud (Santos Fuentefria, 2017).
- Planning of the power system. Like in medium and long-term studies, the grid is planned to adopt the new planned renewable generation. This study informs what would be the necessary reinforcements that should be made; what equipment to buy and where to install it to guarantee the stability of the power system; how to carry out the reactive power compensation. The compensation can be done either by some additional equipment or by

the renewable generation itself with switched power converters. In which case it must be analyzed what type of technology should be installed.

- Impact on the voltage stability. Although this study is carried out in the three previous studies, due to its importance, it is analyzed as an independent study. This study guarantees fulfilment of the grid code and voltage stability. Cuba is an isolated system, longitudinally configured, whose distribution networks are mainly radial. This makes the study of voltage and reactive power compensation a subject of vital importance.

System-wide studies analyze the operation of the power system and balance between the production and the consumption resulting in the stability of the system frequency:

- System operation. This study analyzes how the operation of the power system is affected by the introduction of the VRE generation. Aspects such as generation planning (unit commitment and economic load dispatch), generation costs, maintenance plan, load and generation forecasts, supply of demand and residual load, primary, secondary and tertiary reserves, are taken into account. The final objective of these studies is to guarantee the supply of energy to all consumers with the required quality 365 days a year, 24 hours a day.
- Impact on frequency stability. Variations in the wind and solar generation together with variations in the demand can cause a misbalance between the supply and demand and problems in the system frequency. Carrying out this study guarantees that the frequency remains within the allowed limits. In Cuba, the frequency must be kept below 60.2 Hz and above 59.7 Hz in normal operating conditions. This type of study also ensures that in case of any contingency, the system recovers its frequency to standard values and avoids unwanted disconnections of loads, in other words, blackouts. Several studies have been carried out in Cuba on the impact of renewable sources on the power system frequency and system operation (Filgueiras Sainz de Rozas et al., 2019; Guerra Hernández et al., 2016; Guerra Hernández and Martínez García, 2007; Martínez García et al., 2007; Salgado Duarte, Martínez del Castillo Serpa, and Santos Fuentefría, 2018).

Conclusions

Grid integration studies analyse the impact of renewable generation on an electrical power system. The main objective of these studies is to maintain the stable operation of the system and provide energy to all consumers with the required quality while maximizing the contribution of renewable generation. For this, technical, economic, social and environmental aspects must be taken into account. These studies can be carried out from the local or system-wide point of view, in the short, medium or long term. These studies are extremely important for the development of renewable generation within the energy mix of any country. The next chapters of this section present some of the ongoing work by doctoral researchers from CUJAE, UO and IMMM related to the integration of renewable sources into power systems, particularly the Cuban electrical system.

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III.4. Operation and control of the National Electrical System (SEN) of the Republic of Cuba

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Introduction

The island of Cuba, located in the Caribbean Sea, is a 1250 km long and 31 – 191 km narrow island with more than 3500 km of coastline. The island forms an islanded power system with no interconnecting power lines between any neighbouring power systems. The power generation portfolio in Cuba consists of crude oil and heavy fuel oil (HFO) fired condensing steam power plants (thermoelectric steam power plants), HFO and diesel oil-fueled internal combustion engine (ICE) plants, natural gas-fired combined cycle (CC) power plants (gas turbine + heat recovery boiler with a steam turbine), biomass-fired combined heat and power (CHP) steam power plants, hydropower plants, wind turbines, and solar photovoltage (PV) plants.

From the point of view of its control, the National Electroenergetic System (NES) is operated by the National Load Dispatch (NLD), which guides which generation units must be synchronized to the NES according to a low-cost operation scheme and less environmental pollution (optimal operation). At the territorial level, in the 14 provinces of the country, plus the special municipality of Isla de la Juventud, there are offices that operate and maintain the lines and substations of up to 110 kV that are located in the region under their supervision, while there are others territorial offices that operate and serve the distribution scheme (up to 33 kV) at the municipal level. The 220 kV lines and substations are served, from the point of view of operation and maintenance, by a national company, the Construction Company for the Electricity Industry (ECIE).

The power generation capacity consists mainly of thermoelectric steam power plants of Soviet, Czech, French and Japanese origin. These generation plants are located in coastal locations using seawater for cooling. The most considerable of these plants located in the western and eastern parts of the island are listed in Table 1 (UNE, 2019).

Table 1. Thermoelectric Steam Power Plants in Cuba.

Potencia Instalada	MW
Mariel	270
Otto Parellada	60
CTE Habana	295
Guiteras	317
José Martí	30
CMC (3,4)	316
Nuevitas (3,4,5,6)	420
Felton (1,2)	500
Renté (3,4,5,6)	380
Total	2588

In the western region, northeast of Havana and in Varadero, there is a 500 MW installed capacity of combined cycle gas-fired units built in association with the Canadian transnational Sherritt company. Natural gas used in the units comes from that area, as a byproduct from local oilfields.
As a result of the Cuban Energy Revolution, a significant number of new generation capacity was included in the generation portfolio of the country. The total capacities of these new units are:

a) The internal combustion engines with a total installed capacity of 350 MW of MAN units with 18.4 MW of unit capacity and others with smaller unit capacities of MAN and Hyundai technologies totalling 1050 MW
b) Diesel-fueled power units represent a total installed capacity of 1286 MW of mainly MTU technology.
c) 56 industrial biomass-fired CHP steam power plants at sugar mills in service during the harvesting months (Dec-May) with an installed capacity of 476 MW. Heat and power generation of these plants is used almost entirely to meet the power consumption of sugar production, and they contribute very little to the national power system.
d) The total operating installed capacity of the hydropower sector in Cuba is 68 MW. Of these, 43 MW belong to the Hanabanilla hydroelectric plant and 25 MW to small hydroelectric plants (SHP). These hydropower units are generally not connected to the national power system, but they supply mini-grids of remote villages.
e) 4 wind farms with a total nominal capacity of 11.8 MW.
f) 67 solar parks with a total nominal capacity of 156.4 MW.

Electricity sub-station, Havana

Load control in the Cuban power system

The predominant load in the Cuban power system is the residential load. Typical daily load profiles of the Cuban electric power system during summer and winter times are shown in Figure 1 (UNE 2018). In the graphs it is important to highlight the difference between the winter (red) and summer (blue) profiles In both cases, the curves are characterized by having two maximum consumption points (peaks), with the highest value being observed in winter conditions. The highest peak is due to the cooking hours of the Cuban family (highly based on the use of electricity in Cuba) and greater use of electrical appliances and lighting in homes. These types of load curves are typical for underdeveloped countries where the baseload consumed by industrial and commercial consumers is small, and the ratio between the peak load and the minimum load is high.

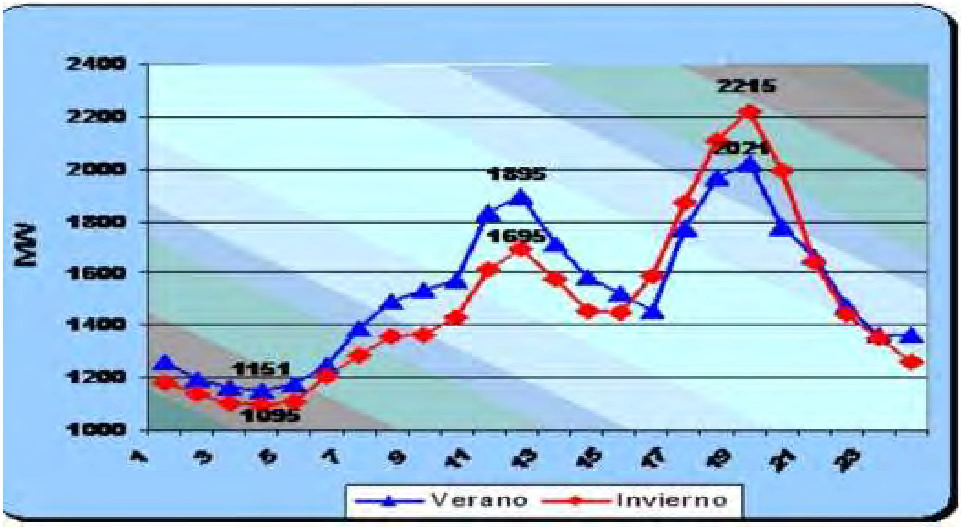

Figure 1. *Typical load curve for Cuban electricity system for summer (Verano) and winter (Invierno).*

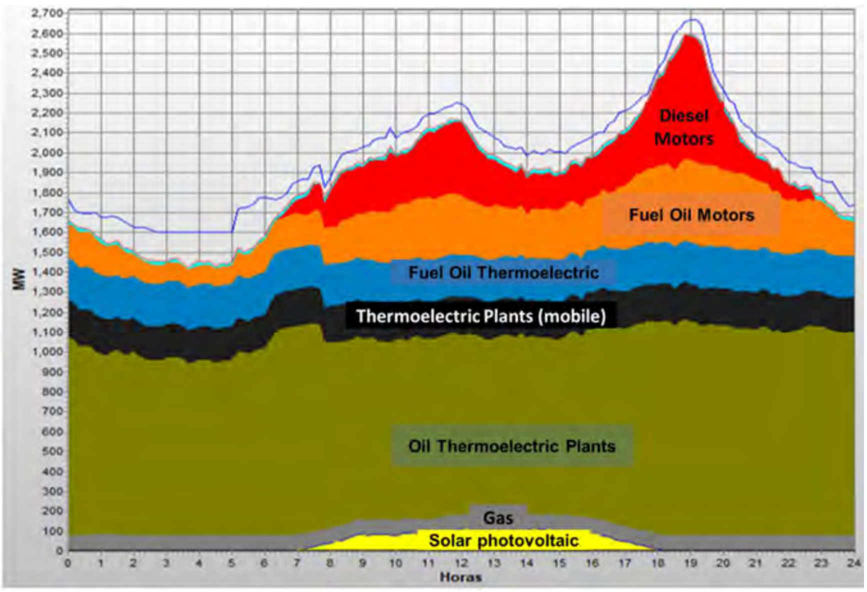

Figure 1b*. Load curve January 2021 (Alonso Falcón, Figueredo Reinaldo, and Sifonte Díaz, 2021).*

Figure 2 shows the actual load curve on a typical winter day. There are two time periods in the load curve when the load control by generation becomes complicated, during breakfast time and in the afternoon. Before Energy Revolution the active power change rate was in the order of 300MW/h but with the massive introduction of cooking with electricity after 2006, the active power change rate has increased even to 500 MW/h, as shown in Figure 2.

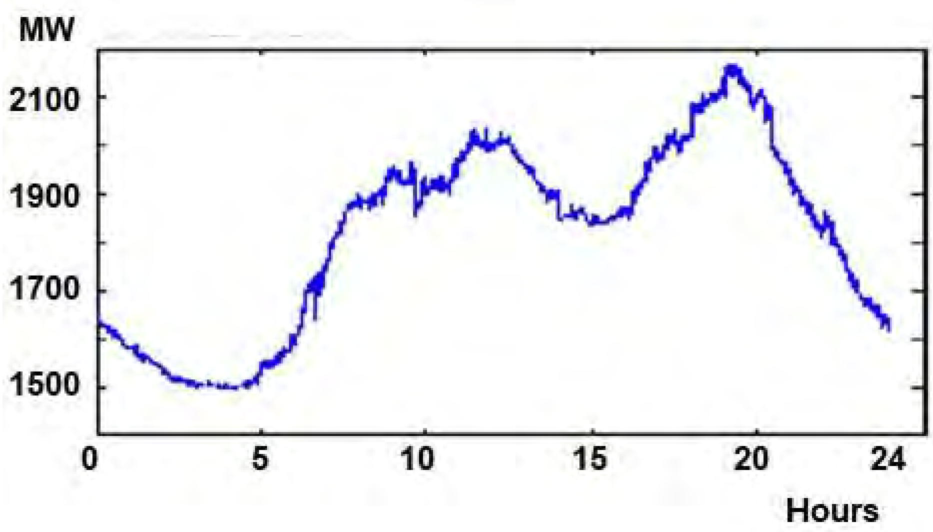

Figure 2. *The actual load curve of the national power system measured every 3 seconds on a typical winter day.*

The load curves with occasionally high load change rates and the big ratio between minimum and maximum loads make it difficult to maintain the balance between the power production and consumption under restrictions of compliance with quality conditions such as system frequency and voltage level. Balancing the load and the consumption becomes even more difficult if one considers that the country's generation fleet is mainly based on more than 40 years old thermal units, most of which were designed to operate as baseload plants. Additionally, they were originally designed to be operated with good quality HFO, but back in the past, they were retrofitted to be operated by low quality Cuban crude oil, which is heavier and has a higher sulfur content. These modifications limit the thermal efficiency and loading speed of the existing thermal power plants.

Short term power system frequency control is divided into primary and secondary controls. The role of the primary control is to react automatically and very quickly, in a few seconds, to measured deviation in system frequency. The primary control units are operated so, that they have the designed up-control and down-control capacity available all the time when the controls are not activated. If the frequency error is caused by an enduring change in load, not just a short load peak, the secondary controls will be activated to compensate for the load change and release the primary control capacity to be able to compensate for new fast load changes. The activation time for secondary control is typically a few minutes. There is also a tertiary control level, which is used when e.g. one power plant unit is unexpectedly stopped causing a long-term lack of power in the system. The activation time for the tertiary control capacity, typically reserve generation units, is a few hours. Starting of the tertiary unit releases the secondary control capacity for new control activities.

Figure 2 shows sharp variations in the load occurring randomly at intervals less than 15 minutes. These load changes are caused by two steel mills with electric-arc furnaces. Cuba´s NLD uses diesel ICE plants to compensate for rapid load changes to avoid non-permissible drops in system frequency. Abrupt increases of load that occur due to the start of new working cycles of electric-arc furnaces in steel mills are regulated by a small group of units assigned to perform primary frequency regulation with incremental rates that take values between 70 and 120 MW/Hz in the periods of minimum and maximum load in the system (Guerra Hernández and Martínez García, 2007). When hydroelectric plants have sufficient water reserves, they are used together with HFO fired thermal units to carry out secondary regulation and recover the primary frequency regulation reserve (CIPEL and UNE, 2018).

Primary regulation reserves are set under the criterion that sudden disconnection of the second-largest unit connected in the system (Felton 250 MW) does not cause automatic low-frequency discharge (LFD). In the event of sudden disconnection of the largest unit in service (Guiteras 300 MW), Automatic discharge by frequency (DAF) is allowed and the service is restored in no more than 15 minutes with the start-up of the reserve diesel units that are maintained as a tertiary reserve. The secondary regulation reserves are set under the criterion that they correspond to the average square deviation of the random variations of the load with the steel mill in service.

Throughout the day, thermoelectric units change power output corresponding to their technical minimums in the night to loads close to the maximum during the peak. It is not possible to start and stop them during the day because of the long intervals of time needed to prepare the starts once the stops occur. In case of maintenance or minor defects, when it becomes necessary to take a unit out of service, another unit is prepared in advance to replace it.

To carry out all this aforementioned operation, the NLD has a DAF scheme that uses fast steps based on df/dt measurements and delay steps that measure frequency, implemented by specialists from the Center for Electroenergetic Research and Testing (CIPEL) that has proven its efficiency in more than 15 years of operation.

Operation of the NES due to the increase in renewable energy sources (RES)

The Cuban National Load Dispatch (NLD) has tools to promote a safe operation of the national power system. Recently, a state estimator was put into service by the French company Schneider, supervised by specialists from CIPEL and UNE, which allows real-time control of the national electric power system. The NLD also uses additional software tools developed by specialists from CIPEL and Central University of Las Villas Marta Abreu (UCLV). The tools utilize the state estimator's database. The software tools allow safe planning of the system's operating regimes and support the dispatchers in making decisions when faced with the system's working conditions in cases of alert, emergency or restoration regimes.

Among these tools are:

- Programs for the ordering (ranking) of contingencies that cause voltage and frequency problems.
- Programs to guide dispatchers in making decisions about corrective measures.
- Programs for the calculation of sensitivity factors.
- Programs for calculating reactive power versus voltage curves for static stability studies
- Training simulator for dispatcher's training.
- Programs for the study of angle and voltage stability under large disturbances.
- Programs for the optimal dispatch of the load in the system.
- Programs for short- and medium-term load forecasting.

The use of the above-mentioned tools enable the utilization of three voltage control zones in the Cuban electric power system and ensures regimes with sufficient reserve of reactive power in each zone. Before dividing the voltage control into the three zones, there were problems with static voltage stability, related to working regimes with no sufficient reactive power reserve in each voltage control zone (CIPEL and Despacho Nacional de Cargo, 2005)

Similarly, developed software allows the operator to determine in which generating units the operation is the most efficient, to reduce the active power transferred by a certain transmission line, or to increase the voltage in a certain node ensuring stable working conditions of the system by post fault outputs of those lines.

During 2019, the electricity generated by Renewable Energy Sources was about 4%. The country intends to increase this value to around 37% by 2030, the only limitation being that the necessary investment is required. Photovoltaic (PV) solar generation plays an important role in this increase, which is expected to reach 2400 MW, wind power around 1200 MW and 400 MW in biomass-fired CHP plants in sugar mills using bagasse and marabou as fuels. The first unit of this type of biomass plant has just been commissioned at the Ciro Redondo power plant in Camagüey with a capacity of 60 MW.

The planned change in the Cuban energy mix will have important effects on system control. This massive introduction of asynchronous PV and wind power generation will significantly reduce the total system inertia, requiring more actions in the frequency control of thermal units that are kept in service. This need comes both from the reduced inertia making the power system more sensitive to frequency changes caused by misbalance between generation and consumption, and increased weather dependent variable renewable energy (VRE) generation by solar and wind power production. (Martinez et al., 2018) The above-mentioned facts necessitates to plan greater participation of these sources in the control of the system (participation in the control and inertial modelling of solar and wind sources). The introduction of battery energy storage systems (BESS) should help primary frequency control and facilitate a greater introduction of photovoltaic plants in the system. Surplus stored battery energy during the day can be used at peak times. The BESS would be charged during low load periods helping to decrease the ratio between peak and minimum load in the system, smoothing the daily load profile making it easier to supply. The economic feasibility of building pumped hydro storage plants is also been analyzed (see section IV.5. Energy Storage: technologies and possible application in Cuban's electric grid).

There is a plan to invest in four new Russian Thermal units of 200 MW each that should have greater participation in frequency and voltage control compared with the current units. There are also introduced new concepts about the control of electric power systems that have been evaluated at an international level, and where the concept of Main Renewable Energy sources (MREs) starting to carry out control actions is being imposed by decreasing the participation of conventional generation units.

New operating conditions of the Cuban power system with the entry of a significant share of renewable sources requires the introduction of new modes of operation that are not currently considered in the approved operating codes. Also, additional studies about new control strategies for generating units enabling them to run robustly in different operation conditions will be needed.

A more detailed analysis of the effects of the massive introduction of renewable generation in the electrical system is carried out in Vazquez et al. (2018). In short and medium-term scenarios, new technologies will increase the control needs in the Cuban national electric power system because of the increased penetration of VRE generation (up to 70% - 100%) in the system. An increased share of VRE generation will reduce the on-line capacity of controllable thermal generation in the system. On the other hand, as electronic power converters replace synchronous generators, system inertia decreases and the dynamics of the system will become more sensitive to frequency variations. Similarly, voltage control and implementation of safety functions in the distributed generation schemes will differ from those applied in the centralized generation scheme, because the direction of the electric current flow in distribution lines may change depending on the state of the system, as discussed in Galván and et.al, 2016).

In recent years, an experienced group of system operators has detected an increase in post-contingency system fluctuations, i.e. problems in power system stability after a loss or failure of a small part of the power system or a loss/failure of individual equipment such as a generator or transformer. This problem shows the need to carry out small signal stability studies, the results of which must be taken into account in system control adjustments, especially related to voltage control by the generator excitation system.

Conclusions

Cuban electric power system is managed by the government-owned power system company Unión Eléctrica de Cuba (UNE). The company is responsible for both power generation and power transmission all over the country. The current architecture of the power generation system of Cuba is mainly based on fossil energy fuelled steam power, an internal combustion engine, and combined cycled gas turbine - heat recovery steam turbine-based processes. This fleet has produced approximately 95 % of the annual electric energy production in Cuba. All this generation is transmitted to the different territories of the country through an electric power transmission system made up of 23 substations and 3,112 km of 220 kV lines and 111 substations and 4,387 km of 110 kV lines, respectively. The load profile is characterized by the power consumption of households with low baseload consumption during nights and high load peaks during mornings and evenings due to cooking with electric stoves. In principle, the current type of power generation fleet should be well controllable to respond to normal load changes in the system. However, in practice, there is a big challenge in load control resulting from the outdated steam power plant capacity with a very limited load-following capacity and high stable minimum load levels of these relatively high capacity units.

The National Program for the implementation and development of renewable energy sources and efficiency, which began in 2014, has set an objective to increase the share of renewable energy sources to 24 % of total electric energy production by 2030. This will require a massive increase in wind and solar PV generation and biomass-fired thermal power generation. A strong increase in variable renewable generation sets new challenges to the operation of the Cuban power system. Outcomes of increased variable generation and reduced controllable thermal generation capacity should be compensated e.g., by energy storages and demand-side response by controllable loads. The transition from a centralized generation scheme to a more distributed scheme sets additional challenges to voltage control in distribution networks and the functionality of power grid security systems.

This chapter discussed these topics and presented some research work carried out about these issues. In summary, to reach the goals set by the National Program to increase the share of renewable energy sources in the Cuban electric power system requires a lot of work starting from the updating of the remaining non-VRE generation fleet, and continuing to investments in a new generation, transmission, storage and automation technology. Setting up the new system will require a lot of expertise to design the new system to meet the local requirements specific in Cuba.

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III.5. PhD Research work

III. 5.1. Damping controller design for a weak power system with high-penetration of renewable energy resources

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Abstract

Electromechanical oscillation damping together with the different categories of system stability and operating constrained assure power system security. Poor oscillation damping can result in blackout or generator fatigue. While modifying the power system operating condition can improve the oscillation damping, it is not economical. For this reason, damping controllers are the most efficient and widely used method to damp out electromechanical oscillation due to load variations or severe faults. This work carries out a damping controller tuning method to be implemented in a weak Electric Power System with a high penetration of renewable energy resources like the Cuban power system. The developed method is based on small signal stability analysis and nonlinear time-domain simulation.

Introduction

During a stable and normal state, synchronous generators operate with an electromagnetic frequency of 50 or 60 Hz. This means that the system's electrical and magnetic quantities are swinging as shown in figure 1 a). The mechanical quantities (speed, phase) could be considered constant, neglecting normal and stable load variations.

However, as a disturbance occurs, energy exchange will be generated between the system rotating parts' kinetic energy, as within the network itself in the form of electrical energy (Ruhle, 2006; Samuelsson, 1997) As a result, mechanical quantities (e.g. generators speed) which were initially constant will begin to swing and electrical quantities (e.g. voltage, current) will change their amplitude and frequency creating a time-varying amplitude oscillation known as electromechanical oscillation, as illustrated in figure 1 b).

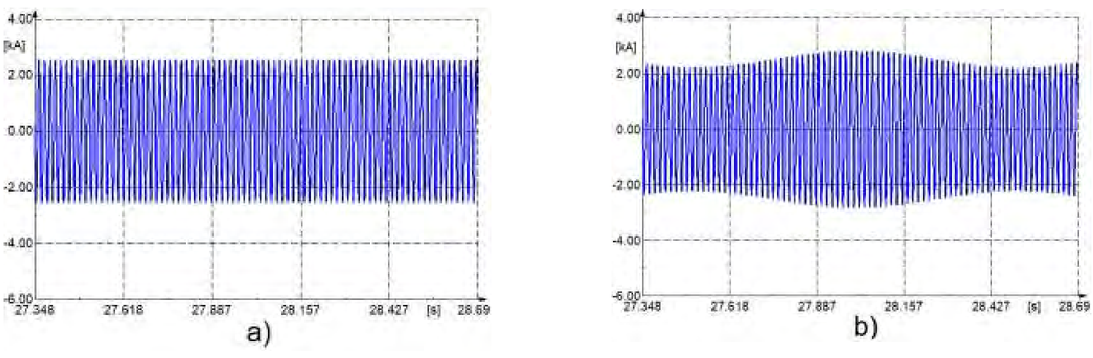

Figure 1. *Line current behaviour, a) stable state normal, b) electromechanical oscillation*

Electromechanical oscillations belong to sub-synchronous oscillations since their frequency is around 0,1 to 46 Hz. This work studies the oscillations whose frequency lies between 0.1 and 3 Hz, known as “low-frequency electromechanical oscillations” (Assi Obaid, Cipcigan, and Muhssin, 2017; Bikash Pal and Balarko Chaudhuri, 2005; IEEE, 2014; Sanchez-Gasca et al., 2007).

The problem of electromechanical oscillations became more crucial with the power systems deregulation in the 80s of the last century (Chung et al., 2004; Kundur and Wang, 2002). These oscillations began to appear between different power system areas and between different countries. This happened because deregulation created an open market for generation and demand and it offered great economic opportunities to generation companies (Kundur and Wang, 2002).

Inter-area oscillation is one of the most critical problems that occur in the power systems since it limits the power transfer capability of transmission lines and threatens the stability of the power system which may result in partial or total blackout (Canizares et al., 2017; Kundur and Wang, 2002; Ruhle, 2006; Samuelsson, 1997). The blackout does not only yield countless economic losses but also creates distrust and fear among the people. One example is the Indian blackout in July 2012 affecting nearly 600 million residents and lasted for about 15 hours. The blackout is due to the inter-area oscillation and poorly calibrated damping control which caused undesired relay operation and worsened the power system disturbance. As a result of this power loss, railways, airports, passenger trains and traffic signals were all shutdown causing commotion in business areas. Moreover, hospitals without reliable power back up supplies had to endure 3 to 5 h of no power (Parihar and Bhaskar, 2018). Unfortunately, as the current power systems are operated close to their operating limit, the risk of inter-area oscillation to occur is becoming higher.

Electromechanical oscillation damping is commonly analyzed using small-signal stability and nonlinear time-domain analysis. Small signal stability analysis allows the identification of some interactions among oscillation modes that would be difficult to achieve from time-domain responses, either from nonlinear simulations or from real-time measurements, which are of fundamental importance for implementing effective solutions to improve the overall damping of the power system. It also provides useful information for determining the generators with significant contribution to specific oscillations modes and for identifying groups of generators that oscillate in a coherent manner (Chan and Hsu 1983; Gajjar and Soman, 2013; Gibbard et al., 2001; Kundur, 1994; Skogestad and Postlethwaite, 2007). The nonlinear time-domain simulation also complements the analysis of non-linear nature response and transient stability of the power system during a critical fault (major disturbances) (Kundur et al., 2004; X. Lei et al., 2001; Xianzhang Lei, Lerch, and Povh, 2001).

The objective of this work is to develop a damping controller tuning method that will be used for a weak Electric Power System with a high penetration of renewable energy resources as exemplified by the Cuban power system. Weak power systems are characterized by their poorly meshed grid, low reserve, high power transfer via the transmission lines, low inertia and it is not interconnected with other power systems.

Today, Cuba is committed to the transition towards clean energy and it aims to reach a renewable energy penetration level of 25% by 2030 as can also be observed globally. This will help in fighting global warming by specifically reducing the burning of fossil fuels for energy. However, the transition raises a major concern for the Electricity Union as the replacement of the heavy rotating turbine power plants by solar panels or small wind turbines reduces the power system inertia which combined with the weak Cuban power system may potentially result in the inter-area oscillation problem. In addition, the simulation results related to power system stability analysis performed for the planning show that the risk of oscillations increases with high-penetration of renewable energy resources by the year 2030. Therefore, it is necessary and of importance to analyse systematically the small-signal stability of a power system with a high penetration of renewable energy resources and further design a damping controller to ensure system stability.

The power system is a complex dynamical system consisting of a large number of connected elements, such as generators, FACTS devices, and the controllers such as automatic voltage regulators and power system stabilizers (Klein, Rogers, and Kundur, 1991). This calls for a distributed controller which is scalable with the system's size. Furthermore, the system model and control parameters of these elements are often not accessible (unavailable) which further complicates the task of the (model-based) controller design. Therefore, the objective of this project is to develop scalable and measurement-based strategies to analyze the small-signal stability of power systems and further design a damping controller to damp undesired oscillation under the high-penetration of renewable energy resources.

Research problem

How to ensure a dynamic response with post-disturbance transient damping for a weak Power System with a high penetration of renewable energy resources?

Distribution network transformer

Novelty

The novelty of this research is the development of a damping controller tuning method for a weak Power System with a high-penetration of renewable energy resources and system rotor angle stability.

Importance: social, economic, environmental

Economic importance: The change in the energy mix is one of the fundamental objectives that the Cuban State has outlined as a way to reduce fuel consumption and the pollution related to the production of electrical energy. In this direction, by 2030 Cuba aims at having 25% of energy production from renewable energy sources (RES). This represents a challenge in the stable operation of the National Electroenergetic System (SEN) due to its characteristics, operating conditions and the decrease of inertia of the system due to the presence of RES. Hence, it is of importance to ensure that the introduction of this technology will not create a new SEN operation problem. The present work aims, precisely, to establish a method that contributes to a more stable and secure Cuban' SEN operation in this new scenario.

Social importance: Ensuring a stable and safe operation of the Cuban SEN will allow us to offer a better service to the different sectors of Cuban society, even within the framework of an increase in the economic blockade that the United States maintains against Cuba.

Environmental importance: Ensuring that the new investments in RES allow a stable and safe operation of the Cuban SEN. As a result, this project will contribute to the reduction of CO_2 emissions into the atmosphere.

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III.5.2. Bi-directional multilevel converter for the electric vehicles connected to grid applications

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Abstract

This research focuses on the development of a bi-directional multilevel converter for electric vehicles connected to grid (V2G) applications. In the first stage, the three-phase three-level neutral point clamped (NPC) topology is selected, taking into account the minimum deviation of the output current, the size and weight of the output filter, the total output current harmonics deviations and the minimum number of the component. In this sense, the modelling and simulation of the power converter selected are made. In the second stage, the ancillary and measurement circuits with a corresponding model, simulation and build process were designed. Finally, the first version of the prototype and the experimental was made where the simulation results were validated with the experimental results. The main achievement of this research work is the prototype of the power converter for electric vehicles (EVs) which accomplishes the international standards.

Introduction

The current world is going through a major crisis from the energy point of view. Because of various problems such as the pollution caused by the consumption of fossil fuels for the electricity generation and transportation systems, the growing demand experienced by many countries around the world is increasing. This is mainly due to the achieved technological development. The concern of this increase is not the demand itself but is to satisfy a high percentage using fossil fuels, accelerating the depletion of these resources and multiplying the damage already accumulated to the planet (Bhargavi et al., 2020; Munsi, Pal, and Chowdhuri, 2020; Vardani and Tummuru, 2020). According to Kyoto and Paris protocols in order to reduce greenhouse gases emission into the atmosphere, it is necessary to use new sources of power generation like renewable energies and electric transportation. These new forms of energy must be able to deliver the energy with the same behaviour as using fossil fuels (Chokkalingam et al., 2019; Vujacic et al., 2018; Wang, Yang, and Blaabjerg, 2017).

The use of renewable energy is the main solution to facing the aforementioned problems, since its present advantages with respect to hydrocarbons from an environmental point of view. On the other hand, they are presented as a new paradigm in the control of power systems, since their primary source is intermittent in most cases, which can cause stability problems within the power system. Taking into account the new paradigm, this engineering problem has been studyed in recent years, and the use of energy storage systems is a possible solution that has been raised (Kempton and Tomić, 2005).

Furthermore, one of the main consumers of fossil fuels is the transport sector. Within the protocols' proposes using EVs with zero emissions has been raised. As the present trend suggests, this mode of transport is likely to replace internal combustion engine (ICE) vehicles in the near future. Each of the main EVs components has a number of technologies that are currently in use or can become prominent in the future. EVs can cause significant impacts on the environment, power system, and other related sectors. Currently, power systems could face huge instabilities with enough EVs penetration, but with proper management and coordination, EVs can be turned into a major contributor to the successful implementation of the smart grid concept. There are possibilities of immense environmental benefits as well as the EVs can extensively reduce the greenhouse gas emissions produced by the transportation sector (Un-Noor et al., 2017). Recently and in support of these approaches, the use of these vehicles as energy storage systems is being analyzed. This technology is called Vehicle-to-Grid (V2G) technology and represent a very important research topic currently (Onar et al., 2012).

100% Electric car, Havana

Professor Willett Kempton of the University of Delaware, New Zealand first unveiled the V2G concept in 1997. His article "*Electric vehicles as a new power source for the electric utilities*", revolutionized the studies of this subject at that time. The ideas forwarded by the professor were: to modify the battery chargers of these vehicles and convert them in a bi-directional way, there would be a completely viable energy storage system and the energy stored could be delivered to the electric grid when it was needed. This modification changed the current design and required more computer logic control, but little additional hardware or cost (Kempton and Letendre, 1997).
In this scenario propound by Professor Delaware, power electronics play a fundamental role because it will be responsible for providing the methods and techniques to interact these vehicles with the electric power system. This efficient interface should allow to charge batteries as well as to deliver energy to the electrical power system, when the system will operate as a V2G, guaranteeing in both modes the circulation of reactive power needed at each point to maintain the

quality of the energy. Therefore, any power electronics system for such purposes must allow the bi-directional flow of energy with the sinusoidal current of low harmonic content. If a residential connection is considered, then the car operates as a Vehicle-to-Home (V2H). It must also be capable of delivering sinusoidal voltage in case of temporary failure of the primary source (Czapski, 2017; Madlener, Marano, and Veneri, 2016; Mohapatra, 2018; Un-Noor et al., 2017; Verma and Singh, 2017).

The previous analysis showed an indisputable opportunity to develop distributed generation systems using mobile energy storage systems such as electric or hybrid vehicles, helping to reduce the transport problems in Cuba (Díaz Santos, Fernández, and Corral Martínez, 2013; Díaz Santos, R et al., 2018).

Research Problem

How to design and build a bi-directional converter with multifunctional input that allows both the single-phase and three-phase connection of electric vehicles (V2G technology) to the electric grid?

Research Objective

Build a bidirectional converter on a laboratory scale with multifunctional input that allows connecting electric vehicles to the electric grid, complying with international standards.

Preliminary hypothesis

Having a bidirectional converter with multifunctional input for the connection of the electric vehicles to the electric grid that complies with international standards. In addition, the converter should be economically more viable than existing ones, will be allowed to reduce or eliminate imports of this kind of technology in the country, and could start the process of introducing electric vehicles into transportation systems.

Expected Results

1. **Theoretical:** Modeling and simulation of bidirectional multilevel converter topologies that allow the connection of electric vehicles to the electric grid, complying with international standards.

2. **Practical:** Prototype of the bidirectional multilevel converter for V2G applications.

The current and scientific novelty

As a contribution to the knowledge, we have the non-existence of a device with multifunctional input for the connection of the V2G in Cuba. Likewise, it has the possibility of connecting both a single-phase and three-phase system with the same topology, with a control algorithm that will be carried out using classical techniques such as the sinusoidal pulse width modulation (SPWM) and also the utilization of field-programmable gate array (FPGA) as the brain of the whole process.

Economics, social and environmental impacts of the research work

From the economics point of view, the impacts of the research work are visible in many ways. One of them could be the cost savings that generate substitution of the conventional vehicles by electric cars. The problem with substitution itself is the necessity to have a powerful infrastructure that could allow the development of a bi-directional converter for the charging stations in an easy and cheap way. It's necessary to take into account that the aforementioned infrastructure isn't cheap, and if you have the possibility to reduce the costs by introducing your own core, the impacts of that savings could increase exponentially. Besides, it is necessary to know that each vehicle can have a power converter inside for home applications. The proposed bi-directional converter could substitute this onboard power converter without many changes in the car, and this could be another source for cost savings in the future, with the corresponding technological independence (Bhargavi et al., 2020; Chokkalingham, Padmanaban, and Blaabjerg, 2018; Madlener et al., 2016; Vardani and Tummuru, 2020).

Moreover, the V2G technologies can be a solution as a mobility storage system that could be considered to make ancillary services in the electric power system. The idea is that it could possible to reduce the number of generators using V2G technology, and reduce the need for consumption of fossil fuels.

From the environmental point of view, the impact of the research work is marked by the aforementioned substitution of conventional cars by electric vehicles. In that sense, we can say that the electric vehicle is an alternative transport method, producing zero exhaust gases and minimal noise, allowing the reduction of greenhouse emission gases. They utilize driving capacity from electric motors and batteries, which has higher efficiency (four times more efficiency) and lower operating costs than a conventional internal combustion engine, these contribute to less fossil fuel consumption (Bhargavi et al., 2020).

From the social point of view, the impact of this research work can be seen in order to contribute to saving expenses in the infrastructure. Thereby, this infrastructure could have the possibility to accelerate the transition process to electric vehicles and bring a solution to one of the big problems that exist in our society, the transportation system.

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III.5.3. Method to obtain adequate wind power according to its control to reduce the frequency deviation in isolated power systems with high wind power penetration

Moises Ferrer Vallin & Ariel Santos Fuentefía

Abstract

Rapidly expanding and with well-established technology, wind power has been the most used renewable source of energy in recent years. Introducing wind generators to a power system can cause frequency problems in steady-state operation scenarios. These problems are mainly related to the wind's inherent variability, the wind generator type and the characteristics of the grid they are connected to. These problems can be amplified in isolated power systems. At the present, wind turbines can support voltage and/or frequency due to their ability to regulate their active power output but sometimes this leads to wind power curtailments. An algorithm is proposed to select the optimal active power control mode for each wind farm to provide frequency support according to wind farm availability, conventional generation availability and load state. Also, the proposed algorithm would optimize the active power output in order to reduce power curtailments.

Background

Frequency deviation problems increase as wind power penetration increases in power systems. This is due to how wind power affects the power system's active power balance, which is defined by equation 1:

$$P_G = P_D - P_{WP} + \Delta P \quad (1)$$

Where:

P_G: Generated active power [MW].

P_D: Demand's active power [MW].

P_{WP}: Wind power generation [MW].

ΔP : Active power losses [MW].

These are insignificant compared to generation and demand active power therefore they are usually rejected in a steady-state analysis and will not be considered.

It can be seen that a change in wind power production has to be followed by conventional generation in order to maintain the system balanced. Therefore, as wind power penetration increases, wind power output variations increase their magnitude. Such variations can cause industrial and domestic equipment malfunctions, i.e. motors spinning at speeds other than rated. The maximum wind power that can be installed in a power system is referred to as the wind power penetration limit. Wind power generation values above a system's wind power penetration limit can cause partial or full-scale stability problems, producing blackout and affecting negatively the end user's quality of service.

Nowadays most of the wind turbines (WT) being installed are variable speed wind generators (VSWG). This type of WT can modify the pitch of its rotor blades according to the wind's speed. This allows to seize the wind's mechanical energy more efficiently but also allows to regulate the WT's power output.

The sudden disconnection of one of the conventional generators in an interconnected system will initially produce rotor swings between the remaining units within the same power plant and generators at other locations in the system. This inertial response is started by consuming the kinetic energy stored on the turbine rotor. Before the start of the contribution by the frequency controllers, the kinetic energy in the rotating mass is the only thing that limits the frequency drop (Leelaruji and Bollen, 2015). Therefore, a power system with a large number of conventional generators will have better frequency stability.

Wind power farm, Gibara

Current VSWGs are not connected directly to the power grid but through a frequency converter that controls the power output of the WT while ''decouple'' the generator from the grid. As a result of this, the power grid cannot "see" the generator therefore its inertia has very little or no influence on the grid. This is particularly relevant for islanded grids or isolated parts of a power grid where systems already have low inertia as they don't have many generators, which makes them susceptible to frequency variations as demand changes. Usually, primary and secondary reserves are not subject to change because, in a worst-case scenario, the reserve is defined taking into account the outage of the largest generation unit, not the wind's variability. Only in grids with high

wind power penetration wind generators are needed to support frequency regulation when conventional generation cannot provide primary and/or secondary reserve.
Consequently, an increase in wind power penetration must be met by an increase in active power reserve to support variations in wind power generation as well as load variations. But this comes with an increase in ancillary services costs in order to guarantee power supply security. Ancillary services generally include frequency control, spinning reserves and operating reserves.
Nowadays wind farms can regulate their output power, having the ability to actively participate in the grid’s frequency regulation. They can operate using active power control, which is comprised of three modes or using synthetic inertia.
The active power control modes, showed in Figure 1 (Tsili and Papathanassiou, 2009), are:

- Absolute power constraint: Establishes a maximum output power limit. Prevents the frequency from going over its defined upper limit.

- Delta production constraint: Maintains an active power reserve following the output power curve but with a different operation point. It allows the wind turbine or farm to perform “upward” frequency control in case it's needed by the power system.

- Power gradient constraint: Follows the output power curve smoothing out rapid changes. Helps to maintain the frequency in a stable value.

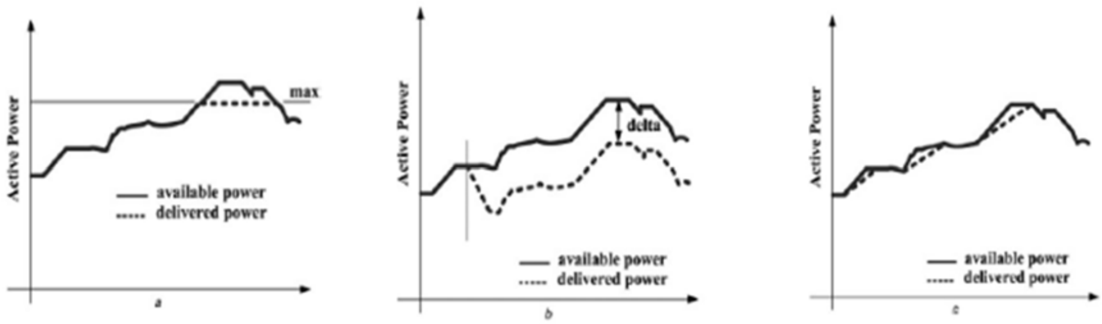

***Figure 1**. Active power control modes: a) absolute power constraint, b) delta production constraint, c) power gradient constraint (Tsili and Papathanassiou, 2009)*

It is important to note that the use of one mode does not exclude the use of another. A wind power plant can maintain a reserve (delta production constraint) while smoothing the power output (power gradient constraint) and limiting its maximum power (absolute power constraint). Figure 2 (Kim and Song, 2015).
Synthetic inertia is defined by Eriksson, Modig, and Elkington (2018) as the “controlled contribution of electrical torque from a unit that is proportional to the Rate of Change of Frequency (RoCoF) at the terminals of the unit”. To put it simply, it consists of the simulation of the inertial response of a conventional generator by a wind turbine. To achieve this, the wind turbine generator torque is modified so it boosts its active power output, dampening the frequency drop. An example of this technique can be seen in Figure 3.

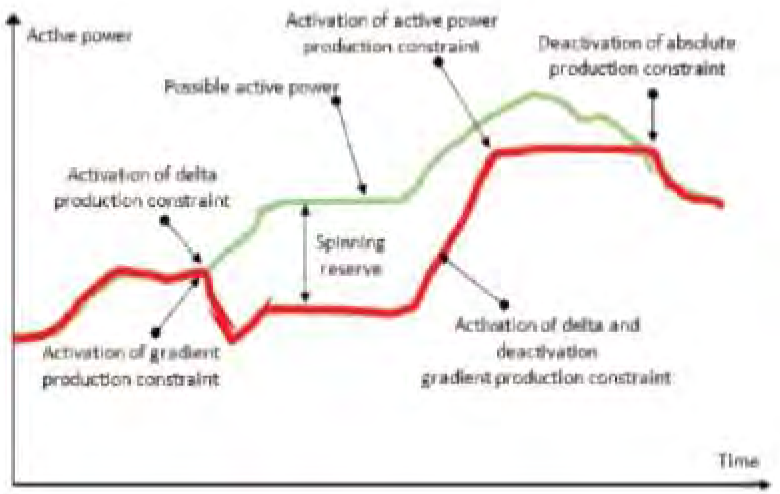

Figure 2. *Active power constraints (Kim and Song, 2015)*

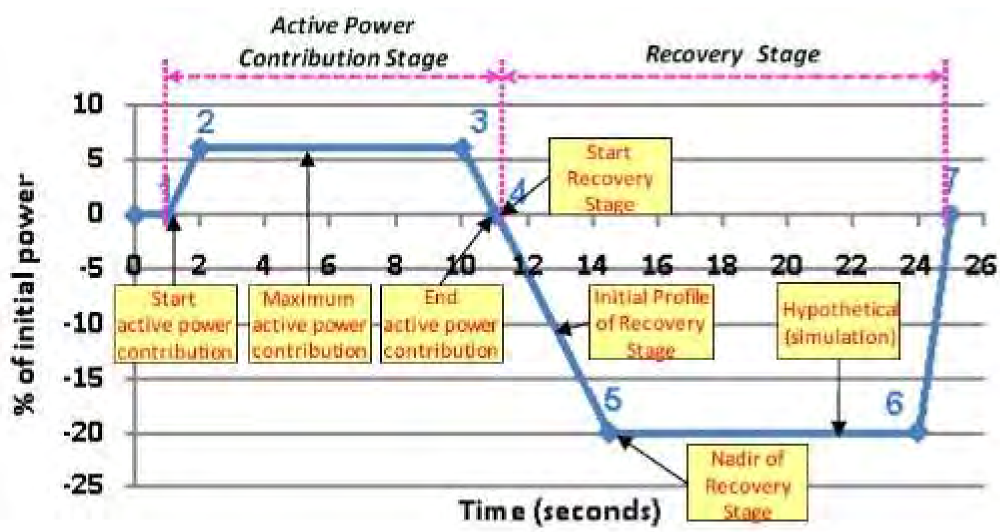

Figure 3. *Hydro-Quebec Transenergie programmed contribution of inertia emulator (Brisebois and Aubut, 2011)*

Grid codes have been established on how to regulate the wind farms output power according to the power system's state and specific characteristics. There were 119 grid codes published as of March 2013 highlighting Denmark's, Ireland's and Germany's due to their experience in the installation and operation of wind farms.

Several grid codes stipulate that wind farms must control their active power during steady-state operation and starting and stopping operations. These requisites refer to the capacity of wind farms to regulate (generally, but not exclusively reduce) their energy production by restricting active power production which is achieved whether by disconnecting wind generators or using the pitch control. Also, wind farms are required to provide active power regulation according to the frequency deviations.

Research problem

What are the adequate output power and the correct control scheme for a wind farm in order to maintain the frequency within the regulated limits in an isolated power system with high wind power penetration?

Novelty

There are several uses for artificial intelligence (AI) in wind power applications. One of its most widespread uses is wind power forecasting, where various methods are used to estimate wind power production based on previously measured data. Some of these methods are: Artificial Neural Networks (ANN), Adapted Neuro-Fuzzy Inference System (ANFIS), Fuzzy Logic and Evolutionary Algorithms (Chang, 2014; Chen and Folly, 2018; Dumitru and Gligor, 2017; Liu, Wang, and Lu, 2017).

Artificial intelligence can also be used to improve the dynamic response of wind turbines (Fatima Zohra et al., 2018), to enhance the blade pitch controllers, to reduce frequency fluctuations by using energy storage systems (Muyeen, Hasanien, and Tamura, 2012) or to regulate the active power output of individual wind turbines within a wind farm (Kazemi Golkhandan, Aghaebrahimi, and Farshad, 2017).

While there are different methods to operate wind farms in order to assist a system frequency regulation, an optimal steady-state solution to select which wind farm(s) can help frequency regulation while it optimizes its active power output is not known. This work's novelty is to develop a method using AI that would provide the optimal active power regulation (if needed) for each wind farm in a power system in order to enhance the system's response to changes in the demand, thus reducing frequency deviations. The method would have to take into account wind farm technology and availability, conventional generation availability, power system reserve and load state, among other important aspects.

Importance

A positive outcome to this investigation would provide a tool that could help determine the optimal wind power reserve in an isolated power system with high wind power penetration. An optimal amount of reserve would help support the system's frequency stability and reduce frequency deviations while seizing most of the available wind potential. This would reduce wind power curtailments which also reduces the operating costs of wind power plants. Also, the annual energy output would be higher which helps reduce carbon emissions. In the case of the Cuban government renewable energy plan for 2030 where more than 700 MW of wind will be installed, this method will help to maintain frequency in the established operation limits, minimizing frequency deviation, avoiding possible blackouts and frequency problems and maximizing wind energy contribution within the Cuban energy mix.

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III.5.4. Evaluation and fault detection in grid-connected photovoltaic systems by analytical methods

Roger Anner Proenza Yero & Luis Vázquez Seisdedos

Abstract

This research focuses on the design of a fault diagnosis methodology that contributes to the improvement of efficiency, maintainability and availability indicators of the Grid-Connected Photovoltaic Systems. A model-based methodology is proposed to be combined with the benefits of data analysis using control charts. In this research, the exponentially weighted moving average is the main focus. To achieve this, we start from the study of the existing mathematical models of the photovoltaic generator and grid connection inverter. Then, a procedure is carried out to quantify the existing operational losses of the Photovoltaic Generator and the mathematical model is adjusted to the real conditions of the system. EWMA (exponentially weighted moving average) is applied to waste to detect and identify the type of failure. The results obtained are validated to show that the proposed approach successfully supervises the Photovoltaic System.

Introduction

Among the alternatives for power generation, Photovoltaic Systems (PVS) are currently one of the most used methods. With the relatively high and stable potential of solar radiation, found throughout Cuba, the autonomy and adaptability of technology to local conditions favour its introduction.

The Program of Development of Photovoltaic Solar Energy in Cuba, executed by the National Electric Union, from the year 2013 included the construction and commissioning of 6 Photovoltaic Parks (PVP) located in Havana, Cienfuegos, Villa Clara, Camagüey, Santiago de Cuba and Guantánamo, maintain a growing trend in the introduction of PV technology in the country.

One of these PVPs is the "Santiago - CIES", it is located in the Abel Santamaría district, Micro 3, Municipality Santiago de Cuba, province of the same name, located in the eastern part of the land occupied by the Energy Research Center Solar (CIES), geographically, is located at the following coordinates, Latitude: 20 ° 00 '75 "and Longitude: 75 ° 77' 07".

The Photovoltaic Park "Santiago - CIES" of 2.5 MWp, is composed of two photovoltaic generators, integrated in its entirety by 10 400 PV modules model DSM-250-C and DSM-240-C assembled in Cuba, grouped into 520 work tables, conveniently interconnected to 130 three-phase grid connection inverters (model SB 17000), manufactured by SMA, with a rated power of 17 kW each. The PVP feeds its energy to the local electrical network at a nominal voltage level of 13.8 kV, through two three-phase coupling transformers.

In 2016, the CIES (Center for Solar Energy Research), carried out a project linked to the national program called Evaluation of the Photovoltaic Park Santiago - CIES of 2.5 MW connected to the National Electric Network. Its main objective was to know the performance in the operation of this because, since its start-up, the technology had not been evaluated. The conclusion gave the following results:

1. There is a deviation of power of the Photovoltaic Generator (PVG) of 7.57%, (See Table 1), lower than the nominal value declared by the manufacturer, which indicates that, as a deviation from the nominal power in the photovoltaic generator, the system produces in a month approximately 23.81 MWh.

Table 1. Average power measured with respect to the number of modules for the SMC (Standard Measurement Conditions: irradiance of 1000 W/m^2, the temperature of 25 ºC).

Measured average power (Wp)	231.96	226.92	224.23	222.19	219.19	212.95
Number of modules	1	8	28	30	27	7
% of the total of modules	1	7.92	27.72	29.70	26.73	6.93
Deviation average (%)	-3.35	- 5.45	- 6.57	- 7.42	- 8.67	- 11.27

2. As for the photovoltaic inverter, a total of 8 (replacement) failures were reported in 2016 with a delay of approximately 6 days, which means a loss of 3.88 MWh, which is equivalent to 1044 MWh.

3. It is estimated that in 2016 the PVP Santiago CIES operated at 91% of its nominal yield, figure 2, therefore, the operational losses of the system in general amount to 25.2 MWh per month.

With the advance of computer control and monitoring, important benefits have been obtained at an industrial level, since routine activities carried out by people have been automated. Human operators often make wrong decisions that cause major failures to the originals. Industrial statistics show that 70% of industrial accidents are caused by human errors (Berbesi 2012).

The software in charge of supervising the processes is the so-called SCADAs (Supervisory Control and Data Acquisition) systems. They are in charge of recording the evolution of a process and detecting undesired deviations of the variables involved, as well as analysing these deviations and making a diagnosis of the situation. In addition, these systems try to solve the problem online and if it is not possible, take the necessary steps so that the error does not happen again.

Even when the PVPs have a SCADA, they only allow the monitoring of the system. This monitoring includes the real-time recording of the process variables, for example, voltage and current on the direct and alternating side, as well as active power at the output of the inverter and the environmental variables (irradiance and operating temperature of the PV module). However, it does not allow the supervision of the system. The SCADAs are capable of obtaining a group of operating variables from the system and visualizing them, but they do not process them in order to detect possible problems that some of the system components present, and depending on this make a diagnosis.

Solar power plant, Abel Santamaría, Santiago de Cuba

SCADAs limitations of the PVP

1. It is not capable of detecting faults that occur at the level of PV modules. Each PV module of 250Wp generates approximately 1,050 kWh, a failure in this component is imperceptible on the part of the operator, so losses for this concept are present for long periods of time.
2. There is no real-time evaluation of the performance of the photovoltaic generator and grid-connected inverter, which leads to insufficient information that serves as a basis for taking maintenance actions and generates false expectations in the planning of electricity production.
3. The SCADA does not have a tool for the management of the information of the historical failures impeding the feasibility studies for the technical quality of the PVP.

In practical conditions, the failures that are inevitable in the photovoltaic system can cause energy losses (efficiency reduction), partial or total system disconnection and even serious safety infractions (Alam et al., 2015). The detection of these in the photovoltaic system is, therefore, crucial to maintaining normal operations by providing early warnings. In fact, accurate and early failure detection in a photovoltaic system is critical to prevent its progression and significantly reduce productivity losses.

Several Failure Diagnostic techniques have been developed for photovoltaic systems. They can be divided into two main groups: approaches based on the history of processes (Mekki, Mellit, and Salhi, 2016) and model-based approaches (Chouder and Silvestre, 2009, 2010; Vergura et al., 2008), obtaining good results in terms of detection and early identification of failures in system level, mainly on the Direct Current (CD) side. For that second group, the existing mathematical models (previously valued for good operation conditions) of the photovoltaic generator introduced (Duffie and Beckman, 2013; de Soto, Klein, and Beckman, 2006) The current restrictions that these techniques obtain have been aimed to determine the number of elements that are in failure (number of PV modules or PV module chains), which lead to an insufficient diagnosis that serves as a basis for taking actions that enable the management of greater efficiency.

Approaches for the diagnosis of failures in PVS

There are two categories to classify the energy losses that occur in PVSs: operational losses and failures (Firth, 2006). The first is inherent in any photovoltaic system. Operational losses are associated with the inconsistency between the nominal efficiency declared by the manufacturer and the real one, the losses of resistive energy in the cables or the losses due to the degradation of the components. On the other hand, failures are associated with malfunctioning or an unexpected change in the behaviour of at least one component of the system.

In Meyer and van Dyk (2004) an active approach is described. In this approach, the I-V curve is studied to detect faults, and the point of maximum voltage and current power is recorded over time. Due to the nature of the sweep of the I-V curves, there is a reduction in the output power during the analysis, and it is not applicable to passive systems studies.

Two studies (Vergura et al. 2008, 2009) consider several identical photovoltaic chains and compare outputs to classify significant deviations. This is done by checking if certain statistical assumptions can be made. Formally the power output differences of the PVG are distributed independently with equal variance. If this is the case, a method known as analysis of variance (Vergura et al., 2009) can be applied to construct a confidence interval for the power output of each photovoltaic array.

Another statistical approach is taken in Zhao et al. (2013) which assumes a set of identical FV chains and tries to classify the deviations of one with respect to the other. This is done by building confidence intervals using different methods: the 3 Sigma rule and Hampel identifier among others.

In the case of knowledge of failures, it is possible to apply supervised learning (Zhao et al., 2012) where a tagged data set containing manually classified measurements is available. This data set can be generated, for example, by measuring the voltage and current of the PV modules operating in fault conditions. The document analyses a decision tree model that takes the available measures and locates the majority of the data set based on a probable classification. The study concludes that the classification performance is very good, but real-life applications are limited because the data set is closely linked to a specific PV installation.

Research problem

There is limited information about the failures that occur in grid connection photovoltaic systems, which results in a decrease in electricity generation

Novelty

With the proposed methodology it will be possible to manage a higher performance of the Grid-Connected Photovoltaic Systems from the installed supervision system. The methodology allows:

• Evaluation of the performance of the Grid-Connected Photovoltaic Systems, from the quantification of the operational losses inherent in the system.

• Detection and the ability to locate the faults that occur on the DC side of the Grid-Connected Photovoltaic Systems.

Importance: social, economic, environmental

The increasing and continuous use of fossil fuels has caused great damage to the environment. Problems such as global warming and the melting of the poles are consequences of the use of fossil fuels. Hence, the investments aimed at the installation of large Photovoltaic Systems for electricity generation become more important every day. In Cuba, there is a photovoltaic solar energy development program that aims to install around 700 MWp distributed in various photovoltaic parks located throughout the country. Therefore, the need to improve the performance of photovoltaic systems prevails. Equipping them with tools that allow them to detect partial disconnections as soon as possible to avoid energy losses is crucial. Based on the above, this study will allow the development of a tool for the supervision of Photovoltaic Systems, which will contribute to the improvement of the efficiency, maintainability and availability indicators of Photovoltaic Grid-Connected Systems.

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III. 5.5. Control strategies with power quality indicator criteria for invertors in grid-connected PV micro-systems

Frank Grau Merconchini, Luis Vázquez Seisdedos & Janette Cervantes Oliva

Abstract

Nowadays the development of photovoltaic energy, as a part of the distributed generation paradigm, has been growing. The diversity of loads, their non-linearity and the penetration of renewable energy sources (RES) with the use of converters, causes a worsening of power quality indicators. The main quality indicators affecting photovoltaic (PV) hybrid systems are voltage and current harmonic distortion, voltage deviation and voltage and current asymmetry in the system. The physical and mathematical models built-in software applications (e.g. under Matlab/Simulink/Simscape) allow the simulation of different control strategies in these systems and propose control solutions that contribute to improving the quality indicators of the supplied electric energy. In this work, simulations of a grid-connected photovoltaic system with a mixed industrial load are carried out using different control methods, aiming at power quality indicators with the purpose of reducing technical losses and operating costs.

Introduction

In order to reduce active power losses in transmission and sub-transmission lines, improve voltage profiles and increase the reliability of the electric power system, new generation units, both with renewable and non-renewable energy sources, have been introduced in the primary and secondary distribution networks. This new configuration of electric power systems responds to the new concept of distributed generation (DG), which can be defined as "a system comprising localized electric power generation, close to the load centre with storage and management of the same, which can work in isolation or integrated to the electric grid, to provide multiple benefits on both sides of the meter" meter" (Castro Fernández et al., 2018).

The random introduction of DG into distribution networks, in addition to guaranteeing an economic benefit, must ensure the reliability, safety and quality of the power supply, for which the technical constraints of the operational criteria and the standards that regulate these indicators for each voltage level must be met. In those DG sites where non-conventional energy sources that may be variable and uncontrolled (such as solar PV and wind) are used, there is no guarantee that the aforementioned operational criteria will be met (Guerra, 2014; Vazquez et al., 2018). The use of RES in DG responds to the country's policy of transforming the energy mix as part of the Sustainable Development Goals (SDGs) for 2030 (Vazquez et al., 2018). In Cuba, it is expected that RES will occupy 24% of the energy mix and solar PV generation will represent 3% of the total energy generated in the country (Guerra, 2014; Vazquez et al., 2018). This represents reaching 700 MWp of installed capacity in 2030 (Guerra, 2014; Vazquez et al., 2018) (see Figure 1).

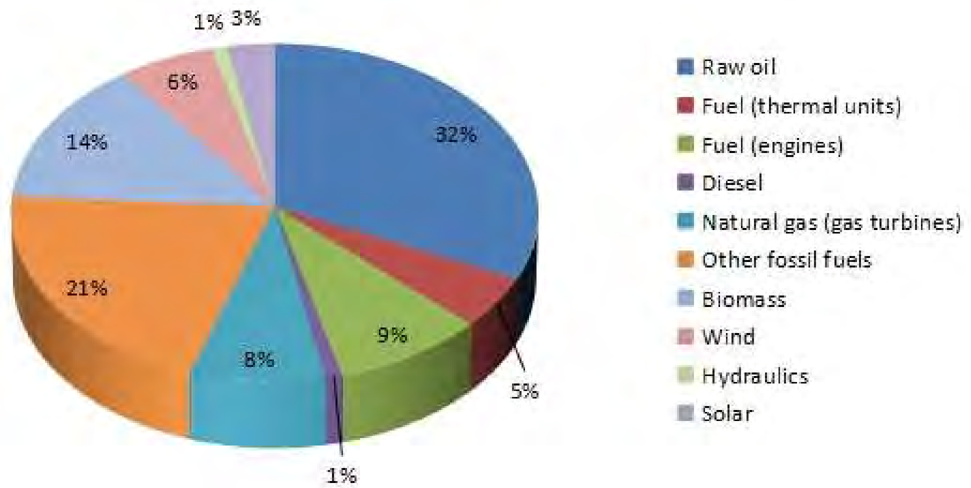

Figure 1. *Energy mix in Cuba for 2030* (Vazquez et al., 2018).

Currently, Cuba produces 95% of its electric energy with the use of fossil fuels. In 2014, the Council of Ministers approved the Policy for the Prospective Development of Renewable Energy Sources and the Efficient Use of Energy, prepared with the purpose of making the most of the renewable resources available in the country (Vazquez et al., 2018).

When two or more power generation systems are combined in a single installation for electric power generation, something called a hybrid system arises. These systems are generally composed of Renewable Energy Sources (RES) and if necessary are supplemented with generator sets, leaving them in most cases only for emergency functions (Stetz et al., 2014).

The advantages of using hybrid systems include the ability to reduce CO_2 emissions associated with fossil fuel generation, and in this way reducing the environmental impact caused by electricity generation (Castilla et al., 2013). Hybrid systems provide significant improvements in those networks that are overloaded by increased consumption. Their implementation does not require major civil works and allows reducing the costs associated with the resizing of low voltage (LV) distribution networks through the coupling of reliable electric power generators that use renewable resources and are sustainable over time. Currently, the most common systems are photovoltaic hybrids supported by a fossil fuel generator (genset) (Castilla et al., 2013; Gurgi et al., 2018; Manikanta et al., 2020). However, hybrid systems with the solar photovoltaic generation that use the electrical grid as their main source of power, are frequent. These systems offer the possibility of reducing the operating cost of the facilities by reducing the electrical consumption from the grid (and even covering the inputs) during the hours of the highest solar radiation (Gurgi et al., 2018; Manikanta et al., 2020; Stetz et al., 2014). In those cases where they have energy storage systems, they can guarantee part of the energy needed during the night. Hybrid systems also represent a backup in the event of power outages in the system.

To guarantee the operation of the system, it is necessary for the energy conversion of a Direct Current (DC) generator system to an Alternating Current (AC) system, which is linked to the (main) distribution network, to feed an AC medium and low voltage electro-energetic system. This requires control elements, inverters, rectifiers, transformers, charge regulators (in the case of having storage systems, for correct charging, discharging and protection), switches, measuring elements and protections.

A general schematic of the hybrid system is shown below:

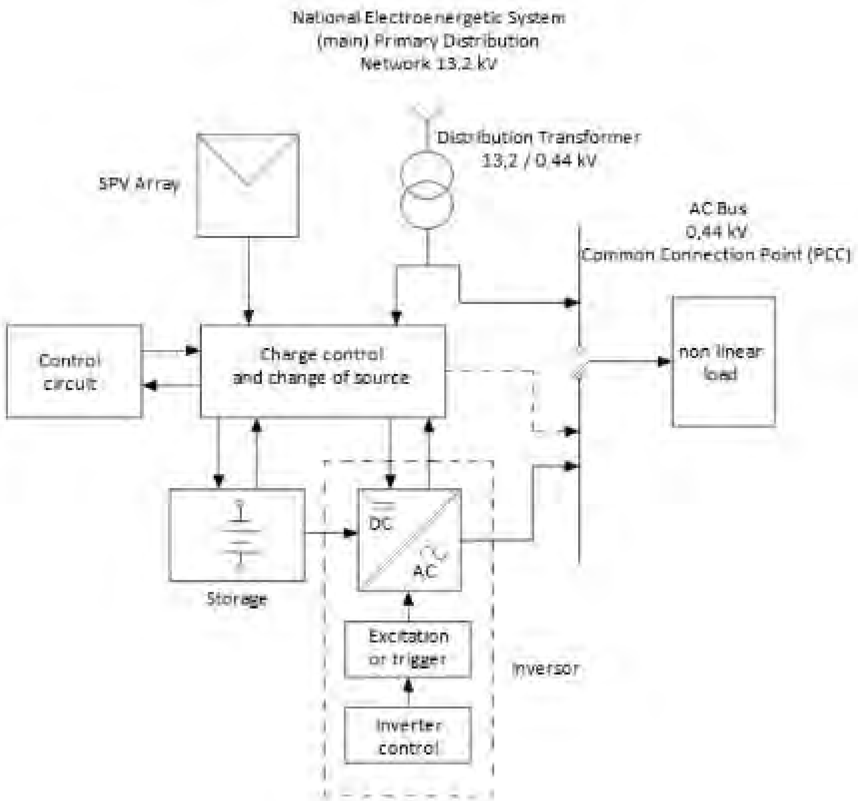

Figure 2. *Grid-connected photovoltaic micro-system.*

The element for the conversion of DC to AC is the inverter. It is normally constructed with an array of semiconductor elements connected in a bridge configuration, using switching elements (transistors) in the form of controlled switches. A passive filter (LC filter or LCL filter) is used to eliminate the ripple in the AC current and voltage signal as well as the peaks caused by the harmonic distortion resulting from the switching of the inverter switches.

In a solar PV system, the waveform of the current and voltage signals on the AC bus can be deteriorated by different causes. Among the causes of poor quality of the supplied electrical power are the following:

a) Non-linearity of the loads downstream of the common point of connection (PCC), which demand non-linear currents from the system and can distort the voltage waveform (Chattopadhyay, Mitra, and Sengupta, 2011; Dugan et al., 2004; Kennedy, 2000).
b) Presence of harmonics and unbalance in the secondary distribution network, which may also be caused by the use of transformers of different capacities forming three-phase banks. Current and voltage distortion in the distribution network may be reflected in the transformer secondary depending on its connection connection scheme (Chattopadhyay et al., 2011; Dugan et al., 2004; Kennedy, 2000).
c) Distortion in the waveform of the voltages at the inverter output, caused by the conversion of a DC system to AC (Chattopadhyay et al., 2011; Dugan et al., 2004; Kennedy, 2000).

Hence, the power quality of grid-connected photovoltaic micro-systems is determined by three fundamental indicators:

1. Individual harmonic distortion and total harmonic distortion (THD: Total Harmonic Distortion) of voltages (THDv) and currents (THDi).
2. The voltage deviation (U_d) for overdeviation (U_{du}) and underdeviation (U_{dd}), given by the ratio between the r.m.s. voltage value at a point with respect to the nominal value for the system.
3. The asymmetry is due to the unbalance in the voltage and current signals (khd), given by the ratio between the null-sequence and positive-sequence symmetrical components for the system voltages and currents.

Figure 3 shows the case study of the Photovoltaic Solar Park (PSFV) of the General Clinical Surgical Hospital of Santiago de Cuba "Juan Bruno Sayas", which has been operating uninterruptedly since 2016, with a total installed power of 100 kWp. This parquet has four (4) three-phase inverters SMC 7000 HV-11, the output of the inverters is connected to the PCC through two transformers of 50kVA each. Each inverter is associated with an array of 96 PFV divided into four parallel branches of 24 PFV with a generation of 250Wp each (UNE, 2019).

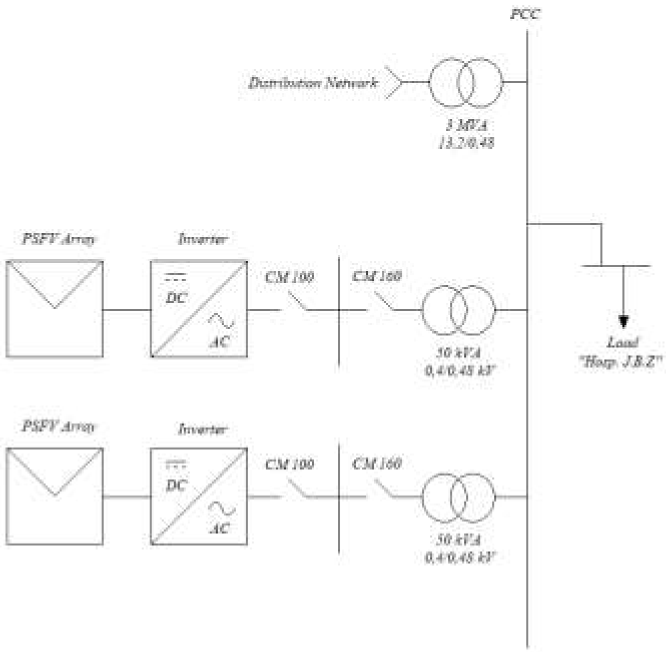

Figure 3. *Schematic of the hybrid system with SPV generation connected to the "Juan Bruno Sayas" Hospital network* (*UNE, 2019*).

The measurements of the study were performed using a three-phase CHAUVIN ARNOUX C.A 8332 network analyzer shows the existence of problems related to unbalance and voltage deviation at the PCC (UNE, 2019).

Similarly, it was possible to verify values of harmonic distortion of voltages and currents above the standard values according to the norms (see Figure 4).

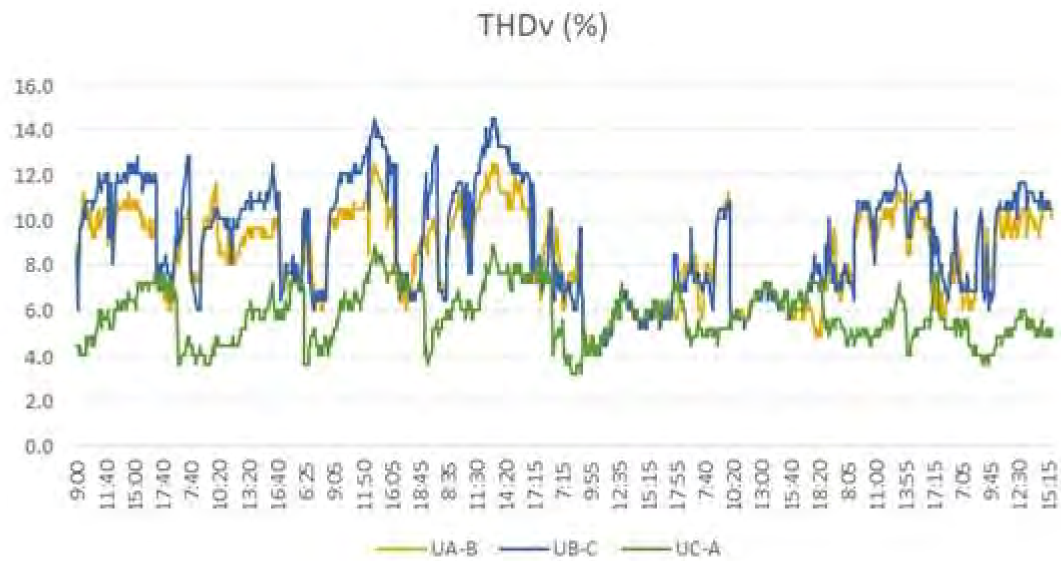

Figure 4. *Graph of Total Harmonic Distortion (THDv) evolution during a typical day at the Common point of connection (PCC) of the "Juan Bruno Sayas" Hospital* (UNE, 2019).

Based on these results and considering that they are common in other studies carried out in the country and on the international scale scale (Castilla et al., 2013; Gurgi et al., 2018; Manikanta et al., 2020), it is necessary to adopt technical measures to improve the quality indicators in these systems and their effects on their operating costs.

When the modification of the installation is not possible or this measure is very costly, it is common to use passive, active or hybrid filters in the elements of the load that have the greatest contribution to the distortion. In hybrid systems, it is possible to improve the quality of the voltage and current signal from the control of three-phase inverters (Castilla et al., 2013) or by using multilevel inverters with a specific connection architecture (Castilla et al., 2013; Gurgi et al., 2018; Manikanta et al., 2020).

The inverter control comes from a unit that forms the control signal from the voltages and currents measured in both the DC Bus and the AC Bus. The Pulse Width Modulation control (PWM) is the most used in these systems and is based on establishing an operating point of the inverter as a function of frequency modulation indexes (m_f) and amplitude modulation (m_a) by comparing two signals, a modulating signal with triangular waveform and an AC carrier signal (see Figure 5).

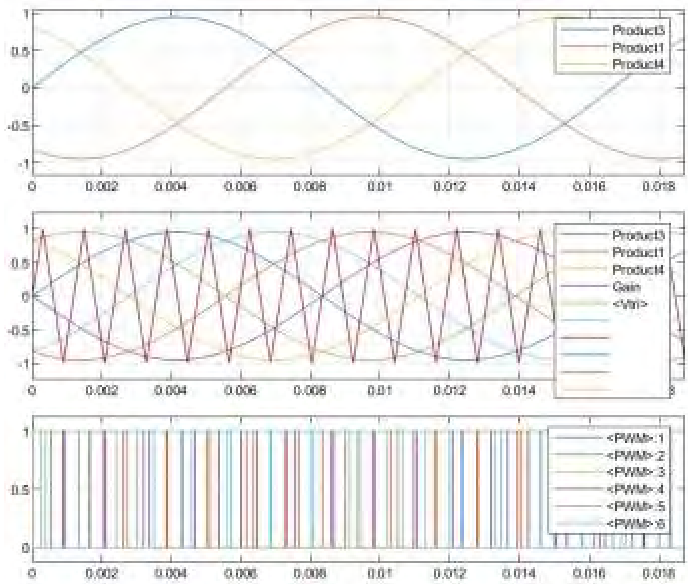

Figure 5. *Pulse Width Modulation (PWM) for a three-phase bridge-type converter.*

An increase in the amplitude modulation index (m_a) results in an increase in the RMS value of the signal and a considerable decrease in the THD of the signal. This is due to the fact that the increase of the modulation index m_a is proportional to the increase of the fundamental harmonic of the inverter output signal (Castilla et al., 2013; Gurgi et al., 2018; Manikanta et al., 2020).

From the spectral point of view, for a m_a less than 1, the number of harmonics with significant values is reduced and these harmonics are concentrated in frequency values that are around 2 to 4 times the frequency of the modulating signal (f_{tri}). When performing this analysis for a m_a higher than 1, the number of harmonics with significant value increases, even when the THD decreases, harmonics of significant order appear close to the fundamental harmonic and these are scattered throughout the frequency spectrum (see Figure 6).

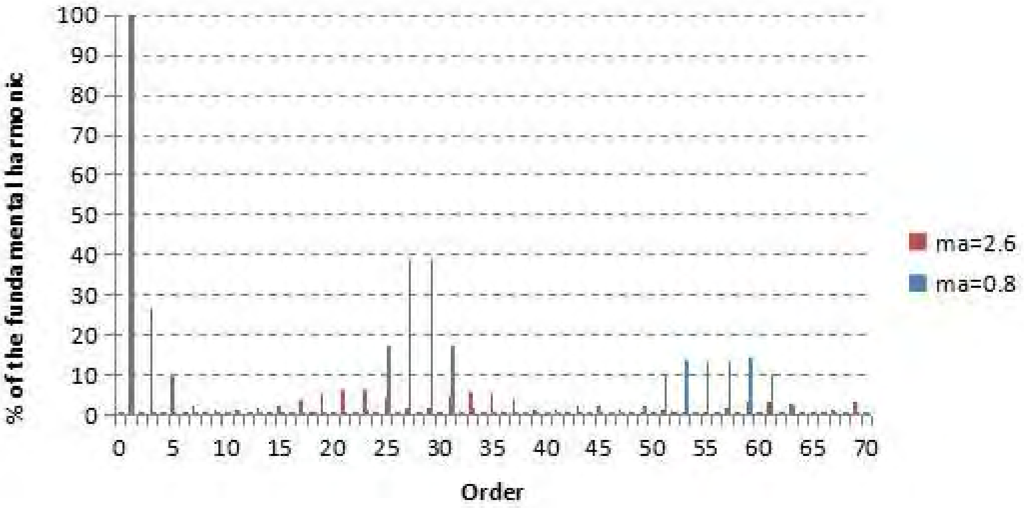

Figure 6. *Comparison of two amplitude spectra for different values of m_a, keeping the frequency modulation index constant (m_f=14).*

Another important element of the control lies in the proper calculation of the inverter output filter, which must include the design elements the considerations established above for the frequency and amplitude modulation indexes set.

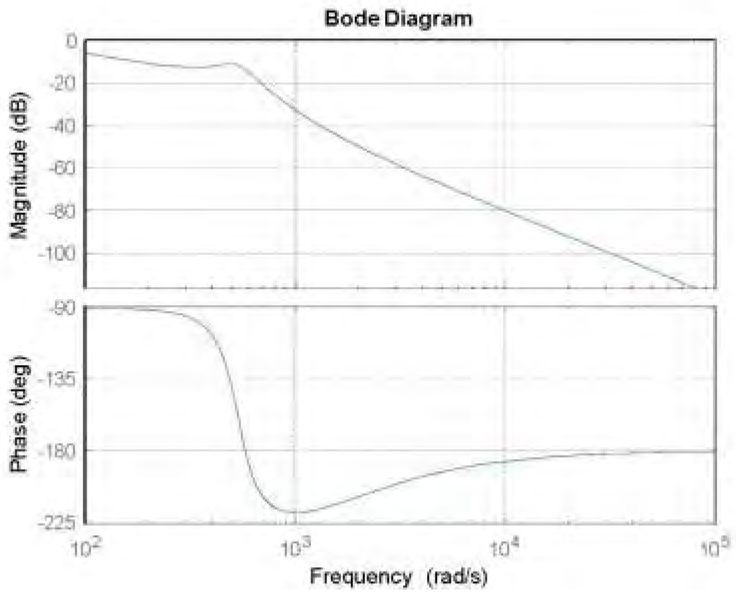

Figure 7. *Bode diagram of the LCL filter at the inverter output. For L=10 mH, C=700μF, Lg=10 mH and with a value of Rd=1 Ω.*

As can be seen in the Bode Diagram (Figure 7), the filter has an attenuation of -60 dB/dec for the high-frequency asymptote, so the higher-order harmonics in the current, products of switching, are attenuated at the output of the inverter. The output of the filter experiences a delay with respect to the input due to the damping function of the filter inductors, for this reason, the signal has a phase relationship of approximately -90° for frequencies below the cutoff frequency.

The physical models built for the digital simulation allow the implementation of different control methods on the inverter as well as the experimental determination and monitoring of the quality indicators in the photovoltaic microsystems (see Figure 8).

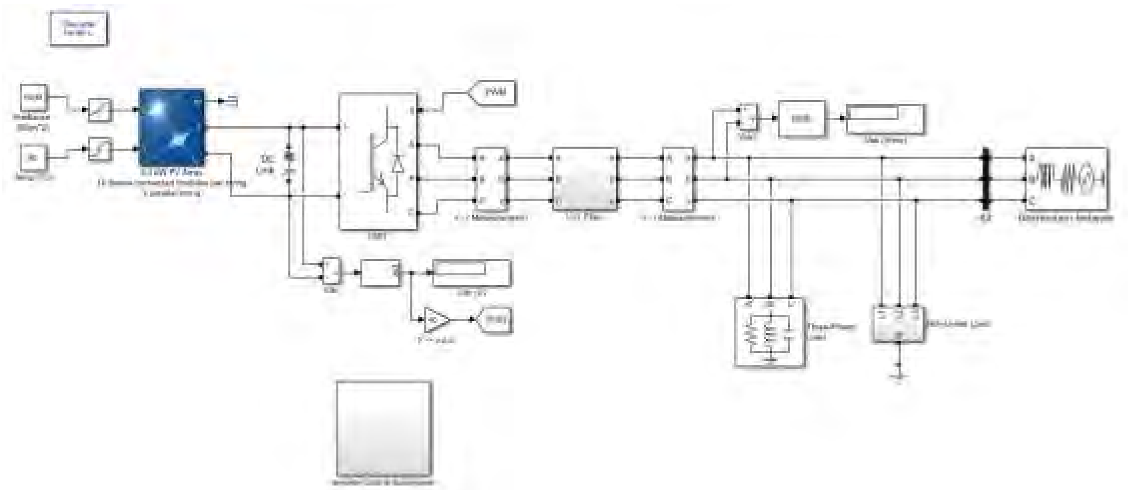

Figure 8. *The physical model for the digital simulation of a grid-connected photovoltaic system.*

The results of the digital simulation of the microsystem reveal high levels of voltage deviation, mainly in phases A and B with 22.7 % and 43.3 % respectively, for a maximum of ±10 % allowed, according to EN 50160 (UNE, 2011). The sequence analyzer reveals a voltage asymmetry value of 40.4 %, which is much higher than the standard value of 2 % according to IEC 61000-2-2 (IEC, 2002), which recommends a maximum value of 2 % for the evaluation of voltage asymmetry in three-phase systems. The total harmonic distortion value for voltage reaches values above 8% (IEC, 2002) in all phases.

On the other hand, the system presents considerably lower power factors in each one of its phases, reaching a power factor of 0.62 in phase C. The microsystem as a whole operates with a power factor of 0.77 backward.

Figures 9 and 10 show the amplitude harmonic spectrum for the voltages and currents at the PCC and the processing in the quality indicators in the hybrid microsystem with grid connection.

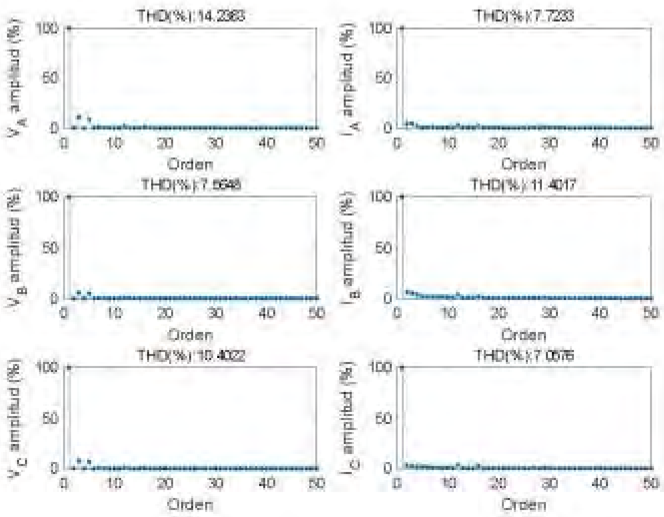

Figure 9. *Amplitude spectrum for voltage and current signals at the PCC of the grid-connected hybrid microsystem (see Figure 8). of the hybrid microsystem with grid connection (see Figure 8).*

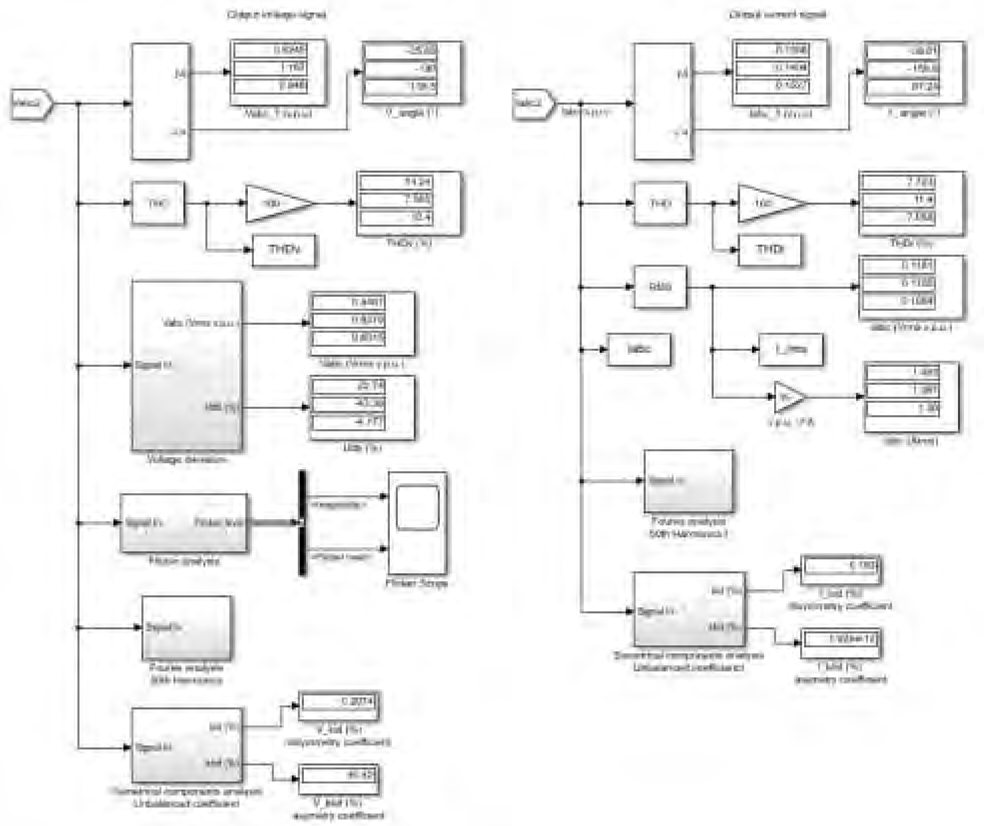

Figure 10. *Determination of technical product quality indicators for voltage and current signals at the PCC of the hybrid microsystem (see Figure 8).*

Among the methods and techniques currently used to control inverters in grid-connected, PV microgrids are the use of Proportional Resonant Controllers (PRCs) in the current control loop, Space Vector Pulse Width Modulation (SVPWM), the use of the Modular Multilevel Converter (MMC) and the use of the Shunt active filter (SHAF) (Dong et al., 2018; Garcia Torres, 2015; Ortega et al., 2016; Sreelekshmi, Prasad, and Nair, 2016; Viswanathan and Kumar, 2017). Each of these methods has advantages and disadvantages for each of the different configurations of the microsystem, as well as to solve each of the problems that may occur in it.

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Research problem

Low power quality levels into the supplied electrical energy, specifically those related to harmonic distortion, current and voltage unbalance and voltage deviation, in hybrid systems with photovoltaic generation and grid connection.

A possible solution to this problem would be given through the design of advanced control strategies of the converter whose output feeds the microsystem with grid connection, in such a way that, as criteria in its performance, the compliance with the regulated limits of the power quality indicators will be taken into account. This would reduce the associated technical losses (such as heat dissipated in transformers, motors, distribution lines, etc., due to copper resistance, magnetic hysteresis and eddy current) and ensure an increase in the sustainability of the investments.

Novelty

The novelty of this research lies in establishing the design methods in advanced control strategies in inverters in photovoltaic microsystems with grid connection, in such a way that they are able to show in their performance at their output in the simultaneous compliance within the regulated limits of the quality indicators of the supplied electric energy, consequently achieving a reduction in technical losses (such as e.g. Copper losses, which are proportional to the square of the currents, as well as additional losses in transformers and rotating machines). This would also affect system operating costs since reducing losses frees up capacity and increases the efficiency of the system. Reduction of operating costs for the distribution company and consequently the reduction of billing costs for the consumer company would also occur. The reduction of losses contributes to the reduction of breakdowns, and by extending the useful life of the equipment, maintenance and replacement costs are reduced.

Social, economic and environmental importance

Some indicators of the quality of the electrical energy supplied, such as unbalance and harmonic distortion, influence system losses, reducing the useful life of its component elements and increasing its operating costs. In secondary distribution networks, losses are concentrated in distribution lines and transformers. The accelerated growth of non-linear loads and hybrid generation aggravate quality indicators and increase these losses which are proportional to the square of the current.

Among the effects of harmonics on distribution circuit elements, the following can be mentioned (Castilla et al., 2013; Gómez-Sarduy et al., 2014; Gurgi et al., 2018; Manikanta et al., 2020; Ruggero Ríos and Sánchez Quintana, 2014):

- Harmonics produce additional losses (Joule effect) in conductors and equipment.
- The presence of harmonic currents may require a higher level of contracted power and, consequently, costs increase.
- The conductors must be dimensioned taking into account the circulation of harmonic currents. Due to the skin effect, the resistance of these conductors increases with frequency. To avoid excessive losses due to the Joule effect, it is necessary to oversize the neutral conductors.
- Circuit breakers in installations are subject to current peaks caused by harmonics. These peaks cause untimely tripping with consequent losses in production, as well as the costs corresponding to the time required to put the installation back into operation.
- When the level of distortion in the supply voltage approaches 10%, the lifetime of the equipment is considerably shortened. The reduction has been estimated at:

▪ 32,5% for single-phase machines
▪ 18% for three-phase machines
▪ 5% for transformers

Based on the results obtained, it will be possible to implement improvements in the electrical system with hybrid systems with photovoltaic generation connected to the distribution network. These improvements will reduce technical losses in the system and consequently reduce the operating costs of the system.

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IV. Energy resources in Cuba

IV. Introduction

Luis Vázquez Seisdedos, Miriam Vilaragut Llanes & Yrjö Majanne

The Republic of Cuba is an archipelago located in the Caribbean sea with a surface area of 109 886 km^2. At the moment electric energy supply in Cuba relies on imported fossil fuels, mainly mineral oil, based power generation. The vulnerable nature of Small Island Developing States (SIDS) calls for a faster energy transition towards Renewable Energy Sources (RES), which is also more conducive to investment (Ashtine et al., 2018).

To achieve the regional Sustainable Development Goals (SDGs), such as mitigation of pollutants and greenhouse gas emissions, a significant portion of new power generation capacity in the Caribbean is likely to come from renewable sources. Hohmeyer and Welle (2018) has shown that Cuba has a vast solar energy resource (over 1 700 00 MW), as well as a very substantial-good wind energy resource (around 19 000 MW). In addition to these two large renewable energy sources, Cuba can utilize a large biomass resource from agricultural and forestry residues, as well as moderate use of energy crops. In addition, Cuba has sufficient hydroelectric resources and areas with more than 300 m of elevation difference, which can be used to build the pumped hydro storage capacity needed for balancing the supply and demand of the electric power system.

However, the variable nature of weather-dependent renewable energy production has been widely evaluated as limiting the ability of small islanded national grids to maintain daily load demand. Isolated grids without stabilizing connections to neighbouring power systems are very sensitive to disturbances in the balance between power supply and demand. Storage systems will play a key role in maintaining a stable electricity supply, allowing a large integration of renewable energy sources despite the ageing grid infrastructure.

Cuba's current electric power system relies mainly on fuels derived from petroleum and natural gas. Cuba has its own oil and gas production, but 30 - 40% of the crude oil used for energy production is imported (ONEI, 2021). Currently, renewable energy-based generation covers only 5.2% of total electricity production. The Cuban electricity system is managed by a national energy company Unión Eléctrica de Cuba (UNE). UNE's total generating capacity is approximately about 6 000 MW. 2 600 MW of generation capacity is based on heavy fuel oil and crude oil-fired steam power plants consisting of generating units between 80 MW and 300 MW. 600 MW is based on natural gas-fired gas turbine units with 50 MW unit capacity, 1100 MW on fuel oil-fired medium/small scale steam and internal combustion engine (ICE) power plants, and 1100 MW on diesel oil-fuelled ICE power plants. Renewable energy-based generation consists of 470 MW of biomass-fired boilers, 63 MW of hydropower (JICA, 2016), 11 MW of wind power, and 217 MW of solar PV.

The Cuban government has instituted a series of reforms in the energy sector focused on balancing costs, improving energy efficiency, reducing risks in energy distribution, increasing international cooperation, and implementing renewable energy technologies. It is estimated that by 2030 the primary energy sources of produced electric energy are: crude oil 32%, other fossil fuels 21%, biomass 14%, fuel oil 13% (engines 9% and steam plants 5%), natural gas 8%, wind 6%, solar 3%, diesel 1%, and hydro 1%. The plan of the shares of different energy sources in 2030 is depicted in Figure 1.

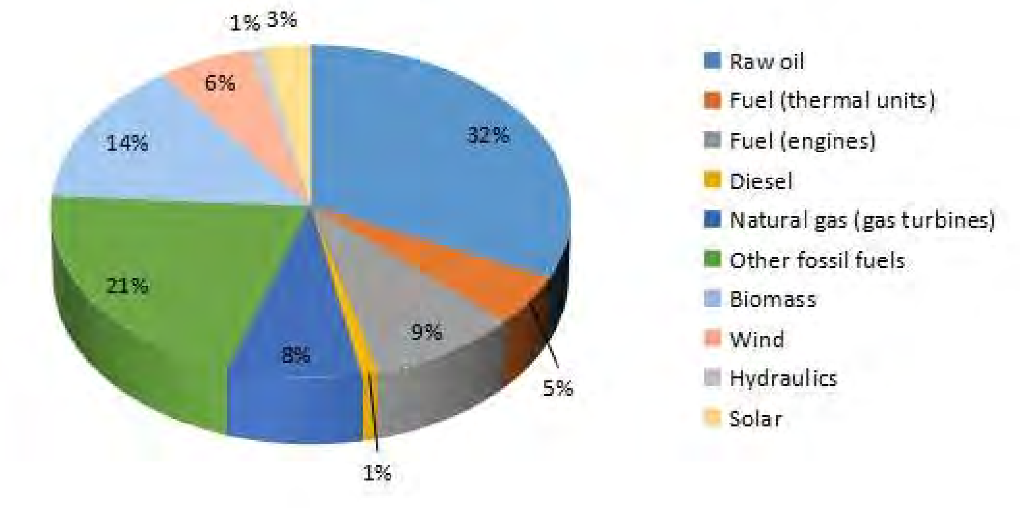

Figure 1. *Electricity mix in 2030* (Montes Calzadilla, 2019).

According to the government policy plan (MINEM, 2021), by 2030 electricity consumption will increase 40%, from 20 TWh to 28 TWh, and the share of renewable sources will increase to 24% of total production. In 2030, the generation resources from renewable sources are expected to consist of 1400 MW of biomass-fuelled thermal capacity, 700 MW of solar PV capacity, 700 MW of wind capacity and 120 MW of small-scale hydropower. The planned growth of the utilization of different renewable energy sources from 2013 to 2030 is shown in Figure 2.

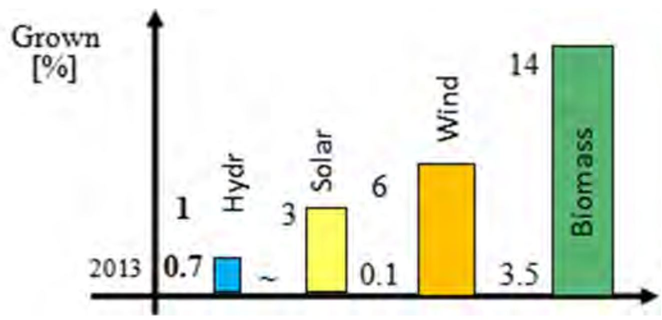

Figure 2. *Increases in installed capacity from 2013 to 2030.*

Assuming substantial economic growth from 2017 to 2040, the current electricity demand of about 20 TWh/a can grow even up to 60 TWh/a in 2040 (different scenarios: 28 TWh/a for BAU (Business as Usual Scenario), 44 TWh/a if other non-electricity consumption in the residential and industrial sectors is converted to electricity, and 60 TWh/a if the entire transport sector is converted to electricity). Analysis by Hohmeyer and Welle (2018) has shown that the combination of 14 500 MW of wind, 8 400 MW of solar PV, 1 500 MW of biogas, 236 MW of hydropower, and 3 000 MW of pumped hydro storage, together with the use of biodiesel in the existing 2 500 MW of diesel generators as ultimate system backup, can supply Cuba's entire electricity demand for a 60 TWh/a scenario including e-mobility and the substitution of natural gas and mineral oil in the residential and industrial sectors.

The increased share of renewable energy sources in the future electricity system poses several challenges to system planning and operation. The weather dependence of wind and solar PV generation increases uncertainty in system design assumptions, which must be taken into account in the decision-making on generation capacity and required reserves, the need for energy storage, control strategy, and system flexibility. Increasing the share of RES in the electricity system increases control needs (load following + variable generation), while the share of controllable thermal generation capacity is usually reduced. Thus, there will be an increased amount of disturbances in load balance to be regulated by a smaller capacity of controllable generation. In addition, replacing a large number of steam turbines or ICE powered synchronous generators locked in the frequency of the power system by wind turbines and solar PV generators connected to the power grid by power electronics-based converters, the power system loses a lot of stabilizing inertia. This makes the power system more sensitive to severe system frequency stability problems. Reduced inertia speeds up the dynamics of frequency disturbances due to an imbalance between power generation and consumption resulting in an increased need for a fast-reacting controllable generation or consumption capacity.

Therefore, the massive introduction of RES in the Cuban electricity system is not only a political issue, but also requires a deep analysis of the system planning methodology, control design and operation issues. Power system designers need new knowledge to be able to face all the challenges posed by the new type of DG power systems with a high proportion of generation from variable renewable sources (Castro Fernández et al., 2018).

Conclusions

The political decision to change Cuba's energy mix involves several issues, including energy economics, environmental issues and energy efficiency. The transition to the utilization of renewable energy sources will reduce the amount of imported fuels and the detrimental environmental impact. In addition, the structure of distributed generation (DG) instead of centralized generation will reduce transmission losses (Bouhouras and Labridis, 2012), and will improve the resilience of the system to hurricane attacks and other locally occurring natural disasters.

The transition from fossil fuels' energy mix to one based on renewable energies is a necessary challenge. The transition to a sustainable renewable energy-based energy system requires new and sophisticated technology. During the transition phase, thermal power generation shall be used to guarantee the operation of the new system and give time to find solutions to possible problems arising from the increasing utilization of variable renewable generation in power production. This new flexible operating environment requires more professionally qualified operating and technical personnel to manage and run the system.

Chapter IV consists of seven subchapters. After this introductory chapter IV.1, Conrado Moreno and Miguel Castro Fernández discuss in chapter IV.2 the potential of wind power generation in Cuba. In Chapter IV.3 Ruben Ramos Heredia, José Emilio Camejo Cuán, Saddid Lamar Carbonell and Dunia del Rosario Barrero Formigo discuss solar PV generation, in chapter IV.4, Jorge Jadid Tamayo Pacheco, Angel Rubio González, Junior Lorenzo Llanes and Angel Luis Brito Sauvanell discuss the role of biomass-based power generation. In chapter IV.5 Leonardo Peña Pupo, Ernesto Yoel Fariñas Wong and Angel Luis Brito Sauvanell discuss hydropower resources and development, and in chapter IV.6 Miguel Castro Fernández, Rafael Pomares Tabares and Miriam Vilaragut Llanes discuss energy storages. Chapter IV.7 introduces nine energy resources related topics of doctoral theses of Cuban doctoral researchers. The topics are

- Reverse Modelling of Plasma Gasification with Gasification Temperature and Produced Gas H2/CO Ratio Requirements by Jorge Jadid Tamayo Pacheco
- Mathematical model of the mixotrophic culture of the microalgae Chlorella SP. in an outdoor falling film photobioreactor by Orlando Alfaro Vives
- Lifetime prediction models of White LEDs used in lighting by Diego de los Angeles Fernández Labrada
- Methodology for the Dimensioning and Optimal Location of Photovoltaic Systems (PVS) with evolutionary algorithms by Adrian Romeu Ramos
- Effect of dust accumulation on the performance of photovoltaic modules installed in the mining and industrial environments by Liomnis Osorio Laurencio
- Maximum Power Point Tracking using artificial intelligence technique in photovoltaic systems by David Díaz Martínez
- Improve the energetic efficiency in micro-HydroPower Plants in autonomous regimen controlling the frequency with AC-AC converters by Henry Bory Prévez
- Procedure for the efficient operation of a fuel oil generator system by Aliniuska Noa Ramírez
- Increase of electricity quality and water savings in autonomous micro-hydropower through a combined flow-dump load control procedure by Leonardo Peña Pupo

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IV.2. Wind energy in Cuba

Conrado Moreno Figueredo and Miguel Castro Fernández

Introduction

By June 2014, the Ministry Council and the National Assembly approved the "Policy for the use and perspective development of Renewable Energy Sources and Energy Efficiency 2014-2030". The Council of Ministers and the National Assembly also approved the Implementation Schedule of this strategy. In this schedule, the projection for installing new electricity power plants is the following:

- 13 Wind Farms: 633 MW
- Solar Photovoltaic farms: 700 MW
- 19 Sugar Cane Biomass Power Plants: 755 MW
- 74 Small Hydropower Plants: 56 MW

Currently, the share of renewable energy in the electricity generation matrix is 4%. The national target is to achieve 24% by 2030 (6 times more) on the basis of previous goals using renewable energy technologies. The energy generation will be nearly 7 245 GWh per year. This jump will require around 3,700 million USD for imports. With this amount of renewable energy producing electricity, 6 million tons/year of CO_2 will not be released into the atmosphere. Finally, fulfilling this objective will contribute to mitigating climate change and protecting the environment.

Current situation of wind energy in Cuba

The total wind energy capacity installed in Cuba until the end of 2019 was 11,7 MW. Four wind parks are in operation in the country:

- Turiguano Wind Park: 0,45 MW
- Los Canarreos Wind Park: 1,65 MW
- Gibara I Wind Park: 5,1 MW
- Gibara II Wind Park: 4,5 MW

By the next 14 years, 13 wind farms are planned to be located in the eastern part of the island. Nowadays, the Cuban wind market is dominated by the Spanish technology Gamesa (about 44 % of total installation). Others are Goldwind (38%), Vernegt (14 %) and Ecotecnia (4 %).

Model of a wind pump

Wind energy resource

At the end of 2005, the government decided to acquire and install 88 wind measurement stations with sensors at 10, 30 and 50 m in height plus 12 reference stations at 100 m in height. The data collected by these stations together with the set of historical data from the 68 National Meteorological Network stations and the process carried out in order to identify the windiest areas have revealed that 8 zones located in the eastern side of the country are suitable for installing wind parks where it is possible to achieve 633 MW. Figure 1, below, shows the zones where the future wind parks are planned. The mean wind speed in these zones is higher than 6 m/s and the density power is higher than 250 W/sq. m. There are other areas that are currently analyzed as well.

Cuba has started studying its wind energy potential in the mid-1990s. A 2006 version of the Cuban Wind Map has been elaborated by Cuban professionals. This Wind Map offers a detailed distribution of wind resources. It is the first characterization of the wind energy potential in the country.

Based on the application of the Riso Laboratory micro-scale WASP model and using the surface data from 40 meteorological stations belonging to the National Meteorological Network, this wind map has been elaborated. According to this Wind Map, the theoretical wind potential is around 5 000 MW and 14 000 MW.

By 2013, a new version of Wind Map was launched by the National Meteorological Institute in the framework of the 12th World Wind Energy Conference and Exhibition (WWEC2013) in Havana, Cuba.

Future and perspectives

By the next 10 years (till 2030), 13 wind farms are planned to be located in the eastern part of the island. The current situation of the 13 wind parks is the following:

- Funds have been obtained for 3 wind farms. One of them is under construction (Wind Park Herradura I)
- A foreign company signed a contract with the Electric Union of Cuba for installing 7 wind parks.
- The negotiations of the rest wind parks are in advance.

Figure 1. *Location of planned wind farms.*

There is not a declared policy focused on small and medium wind turbines therefore the use of these technologies is in stagnation despite that there is a large market in different sectors: industry, tourism, electrification of communities, agriculture, etc.

The use of windmills for water pumping is a tradition in Cuba. Nowadays more than 10 000 wind pumps are in operation in the country and the development is in progress.

The interconnection to the network of wind farms in Cuba

The Guidelines of the Economic and Social Policy of the Party and the Revolution (PCC, 2011) were approved in the 6th Congress of the Communist Party of Cuba in April 2011 and endorsed as the Law of the National Assembly of People's Power in December of the same year, they raised in article 247 the need to "… promote the use of different renewable energy sources… prioritizing those that have the greatest economic effect ...". The massive introduction of renewable energy sources introduces several challenges within the National Electroenergetic System (NES). Given the intermittent time-varying nature of the projects such as wind energy and the integration process into the NES, it should not be forgotten that even though there are advantages in its use (it is a form of generation that can be friendly to both the consumer and the environment, requires a shorter construction time and its costs are currently competitive), there are other elements that must be taken into account consider:

- Sites with higher winds are generally located in remote areas, so an adequate infrastructure is required to bring the power generated by the wind to the load centres.
- Normally the power flow patterns and the dynamic characteristics of the system must be changed when large-scale wind farms are integrated into the electrical system.
- Flow studies must be carried out, both for normal operating conditions and in contingency situations, to analyze the potential overload of the transmission lines, as well as studies on the dynamic stability of the system with the introduction of the wind farm.

This is why the integration of wind farms in each country has its own rules, adapted to the type of electrical system and its particular characteristics. For example, regarding voltage regulations at the connection point of wind farms with the grid, the German Electricity Company VDEW (Verband der Elektrizitätswirtschaft) states that sudden voltage changes (in% of the nominal voltage at the point connection) cannot exceed 2%, while Eltra (Denmark) raises 3% as a limit (Ackermann, 2012).

The Cuban NES has certain conditions, associated with its topology or configuration, that characterize it as a weak system. For this reason, regardless of whether the possible penetration of wind energy into the NES could be defined with studies on a scale of the entire NES, reaching the steady-state and dynamic analyzes of the entire system, some specialists consider essential, on the one hand, exploit the characteristics of the DG in Cuba. This allows working and operating regional systems in the form of an intentional island if necessary (which has already been tested and demonstrated with the use of fuel and diesel generators). And on the other hand, this evaluates the interconnection conditions of renewable energy sources (RES) in each node to exploit said connection in a stable and efficient way, both in conditions of the entire system and in conditions of (intentional island or not) for what which is necessary to analyze the behaviour of the microgrids. They are created in this way with the presence of wind technology under different conditions of the same: stability of the steady-state tension, transient voltage behaviour, stability to small disturbances and frequency stability. It should not be forgotten that the integration of wind energy to the Electric Power Systems (EPS) presents greater challenges in those countries where there are control problems, limitation of interconnections and lower load levels, characteristics that closely resemble the conditions of the Cuban NES.

Regarding the use of interconnection methods (alternating current and/or direct current), which are used internationally for the integration of wind farms in EPS, in Cuba both could be used, especially if the possible interconnection is considered. Of the current isolated electrical systems, which are operated in the tourist poles located in the northern and southern banks of the archipelago, with the Cuban NES, and even the electrical system of Isla de la Juventud (which has very particular characteristics and is somewhat differentiated from rest of the systems isolated from the above-referenced mains), interconnections that, due to the power capacity required to transmit and the distance between the keys and islands with the largest island in the archipelago, can be technically and economically justified in direct current. This would allow delivering energy to said territories from wind farms located in the territory of the main island.

Regarding the use of different wind turbine technologies, the results obtained, both in the studies carried out internationally and in the studies that have been carried out in the Isla de la Juventud electrical system in recent years, allow us to suggest that the integration of the wind turbines of the variable speed type are capable of providing greater regulation to the system. At the time of a failure in an EPS, for achieving a better behaviour, this type of technology must, in any of its design variants, as well as the current ones, be based on full converter technology. They should be the ones that are preferably used in the Cuban NES.

Likewise, the use of Flexible Alternating Current Transmission Systems (FACTS) is a variant that should not be neglected in the integration of wind farms to the Cuban NES, due to the possibilities it offers in relation to improving its regulation, starting from the premise of connection of these wind farms in the transmission system of the NES. This type of technology offers opportunities to control power and increase the useful transmission capacity in the lines based on the control they carry out on the different parameters that govern the operation of transmission systems such as impedances, currents, voltage and the phase angle (Glanzmann, 2005).

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IV.3. Solar photovoltaic energy in Cuba

Ruben Ramos Heredia, José Emilio Camejo Cuán & Saddid Lamar Carbonell

Policy for the development of solar energy in Cuba

As a part of the state's policy and its development plan towards 2030, Cuba has promoted different investment programs to increase the participation of renewable energy sources (RES) in the country's energy mix to 24 %, starting in 2014. With these programs, the installation of more than 2000 MW in new capacities including biomass-based plants, photovoltaic solar technology, wind farms, and small hydroelectric plants, were planned.

The Cuban government has given a high priority to the execution of these programs due to their positive impacts on the environment, as well as their contribution to the country's energy independence. So far, there has been more progress in the solar photovoltaic investment program, which is due to a large extent, to the cheapness of this technology (PVinsights, 2021), the experience acquired in its usage and ease of installation in non-arable areas and building roofs.

The solar photovoltaic investment program was initially planned for the installation of new capacities corresponding to 700 MW of generation by 2030. As of March 2021, 227 MW have been installed in photovoltaic systems connected to the electrical system (ES), of which 215 MW in 72 parks synchronized with the ES and 12 MW installed on roofs and areas belonging to the entities (figure 1). The provinces with the greatest progress in solar power are Artemisa, Granma, Cienfuegos, Sancti Spíritus and Pinar del Río (Alonso Falcón, Figueredo Reinaldo, and Sifonte Díaz, 2021).

The main results achieved to date are reported in Alonso Falcón et al. (2021). All the parks that have been built are generating and allowing the coverage of 6.72 % of the electricity demand at noon, which represents 2.37 % of the total energy consumed in 24 hours in the country (equivalent to the consumption of 147 000 homes). In addition, they maintain a technical availability greater than 98% and their energy production corresponds to that planned in the feasibility studies.

So far, the country has invested more than 250 million dollars in this program with an annual generation of more than 340 000 MWh, equivalent to 88 400 tons of fuel saved. This amount means the non-emission of 285 600 tons of CO_2 into the atmosphere.

Figure 1. *Photovoltaic power connected to the electrical system in Cuba until March 2021* (Alonso Falcón et al., 2021).

At the beginning of 2021, an update of the investment programs of renewable energy sources (RES) was carried out based on the analysis of the results obtained in studies of the Cuban national electrical energy system (NEES). It handled the possibility of assimilating more of these technologies and updated studies evaluation of the potential of the different renewable sources on the island. As a result, an increase in the participation of renewable energy to 37% in electricity production was proposed with a greater role for photovoltaic solar energy (PVs), increasing the generation plan with this technology to more than 2000 MW by 2030 (Extremera San Martín, 2021).

The Sun is the source of renewable energy sources such as tides, waves, biogas, biomass, wind, and solar radiation. Latin America and the Caribbean have the highest solar radiation levels on the planet, from 1 800 to more than 2 200 kWh/m^2/year in the majority of their territories. In Cuban territory, almost 111 000 km^2, solar radiation received every day is equal to the energy produced by fifty million tons of oil. That is the country's energy consumption for more than five years. Figure 2 shows the average normal direct irradiation map throughout the national territory, where a little variation of this parameter can be observed, with an annual average of 1825 kWh/m^2 which corresponds to 5 kWh/m^2/day.

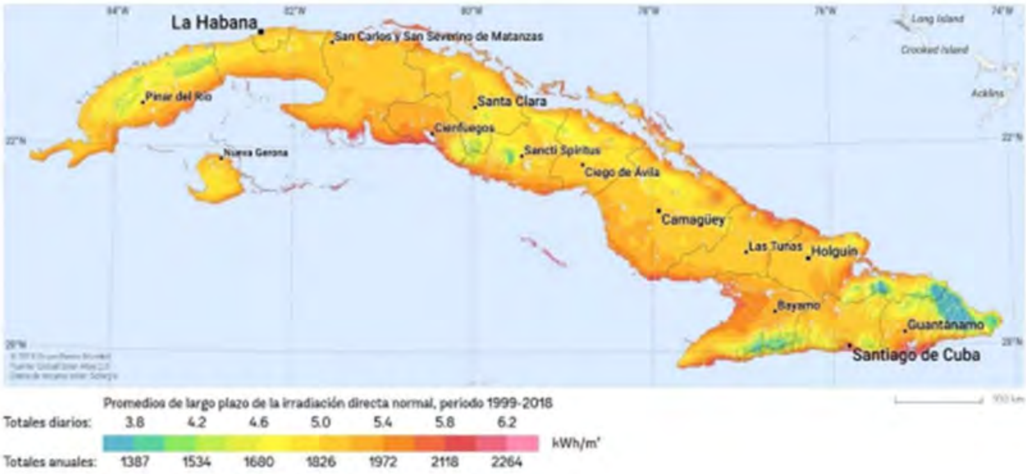

Figure 2. *Map of average normal direct irradiation in Cuba, period 1999 – 2018* (Solargis, 2021).

This article discusses the use of photovoltaic panels at the residential level. It includes the appearance of prosumers, the commercialization in the national market of this type of technology, and the national production of equipment and parts for the development of the use of renewable energy sources. An example of the latter is the factory of photovoltaic panels and electronic components, Ernesto Che Guevara, located in the Pinar del Rio province. This was modernized in 2018 to assume production of 60,000 modules, with a combined power of 15 MW. However, it has not been possible to ensure a production of photovoltaic systems that responds to their demand in the domestic market according to (Extremera San Martín, 2021). Therefore, the residential sector has not yet had access to acquire this product.

It is important to note that the use of photovoltaic systems contributes to the electrification program for homes in isolated rural areas generally difficult to access, where autonomous systems are installed using photovoltaic modules and batteries. To improve the quality of the electricity service of these homes, among other actions, the Electric Union is developing three projects, financed through international collaboration. This can benefit a total of 3 383 homes in 14 provinces and Isla de la Juventud.

Solar power plant, Abel Santamaría, Santiago de Cuba

Types of photovoltaic plants in Cuba. Small and large-scale solar installations. Advantages and disadvantages

In Cuba, over the last few years, two types of photovoltaic (PV) installations have been developed for grid connection systems: centralized and decentralized systems. For the use of one or the other, factors such as specific location characteristics and conditions, proximity or not to low, medium, or high voltage connection points, technological factors, financing, among others, are taken into account. While large tracts of land are used for centralized systems, for the decentralized systems roofs, terraces or small areas of land surrounding the site are used.

The PV installations on the roofs or terraces complement each other and do not limit the productive areas, so they are not an obstacle to the necessary agricultural development of the country. In recent years, PV installations have started in floating solar PV plants. They are somewhat more expensive, although they continue to get cheaper. Among the advantages of this type of installation is the increase in efficiency due to less heating from the solar rays. Variants of facilities are also developed in agriculture, called agro photovoltaic. These installations are two alternatives that may have applications in Cuba. But in the longer term, the largest contributions must be those of utility NEES, plus those on the roofs (Stolik Novygrod, 2019).

Application studies have been carried out at the country level, demonstrating that both system types can be used in conjunction. They can be distributed geographically on the premises. These decentralized applications can be developed in several facilities having lower capacity. They must be integrated according to the conditions of consumption by the residential, commercial, and industrial sectors. Recently, the potential for the use of PV in these sectors has been evaluated (Stolik Novygrod, 2019).

Decentralized systems have the following advantages over centralized systems:

- The operating problems that may be generated in the installation do not affect all users in general, but individually, which reduces the effects of annoyances due to service interruptions.
- They do not require distribution systems to power each home.
- In many cases, the system can be installed on roofs avoiding the use of additional land.

On the other hand, centralized systems have the following advantages:

- Significantly lower installation and maintenance costs.
- They increase the level of benefits, which makes them much more attractive.

Before 2012, only a few demonstrative decentralized Grid Connection PV Systems had been installed in Cuba. They were built to evaluate the technical-economic viability of the technology. As an example, we can cite the 2400 Wp system, installed in the Solar Study Center, located in the Granma province in 2008 and installation in the CIES of 7.5 kWp which was installed in 2012. In this year, the large-scale implementation of centralized grid connection systems began and in the 2013-2014 period, 10 MWp of grid-connected PV systems were installed in the country. At the end of 2019, there were more than 60 parks distributed throughout the country with a total power of 204 MWp (ONEI., 2020).

Solar power plant, Abel Santamaría, Santiago de Cuba

Limitations and challenges to fulfil the plans for 2030

Photovoltaic solar energy has shown in recent times that out of the available renewable resources it has the greatest prospects due to its high independence, great autonomy, low operating costs, and the absence of polluting waste, factors with a great influence on sustainability, as well as it presents the highest adaptability to geographic and climatic conditions.

There are many opportunities to apply the technologies, but barriers must be removed to turn opportunities into realities and to be able to have a guarantee of energy independence and sustainability. In the face of high oil prices and their foreseeable depletion, laying the foundations for future projects of greater scope, the technology, which allows the study, evaluation, and validation of this type of development is the photovoltaic application and its possible gradual generalization in the country.

In addition to the above, there are other opportunities in Cuba (Stolik Novygrod, 2019), among which are:

- Good level of potential and solar radiation throughout the archipelago.
- Achieved technological global PV development.
- High level of economy of scale.
- Reduction of PV costs.
- Increased PV efficiency.

- Increased penetration - integration.
- Existence of Centers and specialists in Cuba.
- Possibility of PV linkages.
- Increase in the facilities of Ministry of Energy and Mines MINEM, and Electric Union of Cuba UNE.
- Existence of other companies to face PV development in the country.

For Cuba to achieve the goal of modifying its energy mix and reaching the renewable energy penetration level of 24% by 2024, photovoltaic solar energy (ESFV) must provide more than 700 MWp. Some barriers must be eliminated before that, the most important of which is to achieve a level of monetary liquidity (using different modalities that include national and international financing) for the financing of the facilities and to achieve an increase in penetration - integration.

Penetration-integration is related to the fact that the percentage contribution of photovoltaic electricity generation to the grid, concerning the total generation among all electrical energy sources, has limits due to its intermittency day - night and its climatological dependence on cloud cover. This defines a maximum level in the penetration and integration of PV power and electrical energy to maintain the stability of the network in terms of voltage and frequency (Stolik Novygrod, 2019).

Another barrier to overcome is the gradual integration achieved between the production and service companies, and the scientific centres, in such a way that it guarantees the permanent technological update, in short, medium, and long term from the application of the processes of Research-Development-Innovation. This would also guarantee the process of training and qualification of personnel linked to technology and decision-makers so that sustainability can be achieved.

This issue was addressed in the guidelines for updating the Cuban Economic Model in the VII Congress of the PCC and it is tacitly established in Article 24, of Chapter I: Economic Management Model (PCC, 2017), which includes research centres that are based on production. The services must be part of the companies or superior business management organizations, in all cases where it is possible so that their research work can be effectively linked to the respective productions. In the Economic and social policy guidelines the need for a close and direct interrelation between scientific centers and companies is modeled.

It is important to highlight that the non-observance of the aforementioned aspects may result in errors in the process of project, design, installation, and maintenance of solar photovoltaic systems, which in general cause increased costs (due to replacements and repairs) and of course economic losses and what is more important, distrust in the technology and its sustainability (given by the rapid deterioration of the operational state of the facilities).

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IV. 4. Biomass energy, resources, technologies, current situation and future perspectives in Cuba

Jorge Jadid Tamayo Pacheco, Angel Rubio González, Junior Lorenzo Llanes & Angel Luis Brito Sauvanell

Introduction

Global energy demand, mainly fossil-based, has maintained its increasing rate in recent decades, resulting in more greenhouse gas emissions (OECD, 2020). In this context, energy from biomass constitutes a solution to both problems. That is why its use has been increased and already in 2019, the global consumption of biomass reached the value of 589 TWh representing an increase of more than four times compared to the 2000 level (IEA 2020).

Biomass as an energy source has advantages related to its versatility and impact on the electricity grid. Besides electricity, also heat, gaseous and liquid fuels as well as other materials and chemical compounds can be produced from biomass. In scenarios dominated by a generation with other variable renewable sources, it can be used to balance the grid since bioenergy plants are controllable and can even be seen as energy storage elements (Arasto et al., 2017). Moreover, due to their geographically distributed location, bioenergy plants contribute to reducing losses in the network (Arasto et al., 2017).

There is a large history of using biomass as an energy source in Cuba, mainly from sugarcane bagasse. Bagasse is burned in the sugar mills to generate the necessary heat for the process and produce electricity for self-consumption. Depending on the mill's energy balance, it is possible to export surplus electricity to the grid. In 1990, a maximum generation of 1 449 GWh was reached, constituting 10% of the total energy consumed in Cuba this year. In 2019, the share of biomass as a primary source in gross electricity generation was 2.5%, with a generation of 519 GWh. Despite this low result, it is the will of the Cuban government to promote the use of biomass as an energy source, setting a target of 14% by 2030.

Due to Cuba's condition as an agricultural and developing country, the organic materials that are not yet used for energy production are numerous. That's why, scientific research has been focused on the estimation of bioenergy energy potential (Colectivo de autores CUBAENERGÍA, 2018; Lores, 1995; Sagastume Gutiérrez et al., 2017, 2018; Suárez-Hernández, et al., 2018). This section aims to summarize and update the knowledge dispersed in the literature about the potential and perspectives of the use of bioenergy in Cuba for electricity production.

Theoretical energy potential of the different biomasses in Cuba. Calculation methods and results

Several biomasses in Cuba can be used as an energy source for electricity production. The most important, traditionally used for such purposes, are sugarcane bagasse and sugarcane agricultural residues (SCAR). Municipal solid wastes (MSW), rice husk, forest biomass and organic livestock residues have been studied by various authors in search of establishing potentials and evaluating technologies, but with discrete practical results of electricity generation (Bravo Amarante et al., 2019; Lesme Jaén et al., 2017; Lorenzo Llanes and Kalogirou, 2019). Due to their small amount, other biomasses such as coffee and corn residues will not be analysed in this work.

In order to calculate the energy potential of each of the studied biomasses, a general approach will be followed, starting from the resource availability and the wet basis lower heating value ($LHV_{w.b.}$) to calculate the thermal potential and then through the efficiency indices of the energy conversion technology used to reach the electrical energy gross production. However, for each biomass there is different information available and the calculation method has to be adjusted. In this way, the potential of the by-products of the sugar industry will be calculated following the method of (Sagastume Gutiérrez et al., 2018) with the incorporation of the SCAR suggested by Rubio González et al. (2019). In the case of MSW, the method of Lorenzo Llanes and Kalogirou (2019) will be used, and in the other biomasses, the idea is to update the potential calculated by Colectivo de autores CUBAENERGÍA (2018) with new data of 2019.

The sugar industry and the use of its installed capacity with marabu

The estimation of the theoretical energy potential of the sugar industry starts from assuming certain considerations about productivity and efficiency indices, see Table 1. This is why it will be considered as harvests in Cuba have an average of 110 days per year, out of this period other organic material must be used to make the most of the installed generation capacity. Then the analysis must be carried out by unifying 2 640 hours with sugarcane by-products and 5400 hours per year with energy crops such as marabu or energy cane. In this study, a cultivated and potentially harvested area of 713 400 ha was considered, corresponding to the area sown in 2017 (Sagastume Gutiérrez et al., 2018). In addition, it is proposed to incorporate the SCAR available in the cleaning centres according to Rubio-González et al., (2019).

Table 1. Indices for calculating the energy potential of the by-products of the sugar industry and marabu.

Technology	Assumptions	Units	Value	Reference
Cogeneration of Sugarcane bagasse, Filter cake, Straw and marabu	Potential Yield	t/ha	90	(Sagastume Gutiérrez et al., 2018)
	Bagasse as cane fraction	%	24	idem
	Filter cake as cane fraction	%	3.3	idem
	Straw as cane fraction	%	7	(Rubio González et al., 2019)
	$LHV_{w.b.}$ bagasse	MJ/kg	7.43	(Sagastume Gutiérrez et al., 2018)
	$LHV_{w.b.}$ Filter cake	MJ/kg	7.72	idem
	$LHV_{w.b.}$ Straw	MJ/kg	10.85	(Rubio González et al., 2019)
	$LHV_{w.b.}$ marabu	MJ/kg	16.30	(Sagastume Gutiérrez et al., 2018)

	Gross Electricity Efficiency	%	28	(Sagastume Gutiérrez et al., 2018)

The thermal installed capacity for combusting the sugarcane by-products P_{th} can be calculated as the ratio of the thermal energy potential $E_{th\ bagasse+Filter\ Cake+SCAR}$ divided by the average harvest hours (see equation 1)

$$P_{th} = \frac{E_{th\ bagasse+Filter\ Cake+SCAR}}{2600} \qquad [MJ/h] \qquad (1)$$

Then the amount of marabu that should be burned to take advantage of the installed capacity can be calculated as in equation 2. Where $LHV_{w.b\ marabu}$ is the marabu lower heating value wet basis, and 5400 are the operation hours with marabu.

$$m_{marabu} = \frac{5400 \cdot 3.6 \cdot P_{th}}{LHV_{w.b\ marabu}} \qquad [kt] \qquad (2)$$

The potential from the sugar industry by-products and marabu is higher than the electricity generation planned by the government for 2030 that is around 30 000 GWh (See Table 2). But this is a theoretical potential, obtained under the premises of theoretical yield and efficiency indices, and maximum use of the planted area and enough marabu near the sugar mills to guarantee a steady supply outside the harvest. This last aspect is critical and some solutions have been studied, one of them is the use of energy cane or other energetic crops.

Table 2. Theoretical energy potential of by-products of the sugar industry and marabu

Biomass	Amount (t)	Thermal energy (GWh)	Electricity gross potential (GWh)	Electricity net potential(GWh)*
Bagasse	15 409 000	32 057	8 976	
Filter cake	2 119 000	4 580	1 269	9 312 -11 972
SCAR	3 595 000	10923	3 058	
Marabu	21 816 000	74 900	20 809	20 725
Subtotal			33 202	30 037 - 32 697

* Considering the electrical self-consumption as in Sagastume Gutiérrez et al. (2018)

Energy cane varieties have proven to be suitable substitutes for forest biomass in biomass-firing power plants. These sugarcane varieties produce twice more bagasse than traditional varieties, they can be cultivated, harvested, and processed with traditional equipment. Besides, their manufacturing process is less energy-intensive, so surplus electricity is greater. A key point concerning energy cane is the necessity of sufficient area in the vicinity of the biomass-fired power plants.

A solution proposed to face the problem created by the distance from the sugar mills to the marabu fields is the pyrolysis of marabu to increase its energy density and at the same time produce electricity (Abreu Naranjo et al., 2012). With this solution, transportation costs are reduced, and therefore, marabu can be harvested in more remote areas.

Municipal solid waste

For calculating the MSW energy potential, two possible solutions are evaluated: combustion of waste in a steam boiler power plant or the anaerobic digestion (AD) of the organic fraction of the MSW integrated with an internal combustion engine (ICE). Both potentials are based on the amount of MSW collected in the country. The assumptions for these energy conversion processes can be consulted in Table 3.

Table 3. Indices for calculating the energy potential of MSW. Incineration and anaerobic digestion of the organic fraction

Technology	Assumptions	Units	Value	Reference
combustion + steam boiler	[a]LHV_{MSW}	MJ/kg	7.43	(Lorenzo Llanes and Kalogirou, 2019)
	Operation	Hours	8 000	
	Gross electrical efficiency	%	25	
AD + ICE	Biodegradable fraction	%	45	(Worrell, Vesilind, and Ludwig, 2017)
	Biogas yield	Nm^3/t_{FM}	150	(Scholwin and Nelles, 2013)
	[b]LHV_{biogas}	MJ//Nm^3	22.7	(Murphy and Thanasit Thamsiriroj, 2013)
	Gross Electrical efficiency	%	40	idem

[a] Based on waste characterization from (Lloréns et al., 2019), [b] Based on 60% (volumetric) methane composition in biogas.

The MSW lower heating value was estimated from the waste gravimetric composition. Havana's characterization was assumed to be a reference for the whole country because of the lack of data on waste characterization per province. Electrical efficiency (25 %) was based on a maximum 673 K – 40 MPa steam cycle due to the flue gas's corrosive nature from waste combustion. It is well recognized that typical electrical efficiency for waste-to-energy plants producing only electricity ranges between 18 – 26 % (Friege and Fendel, 2011; Gohlke, 2009; Kalogirou, 2018).

The organic fraction of MSW comprised the fraction of organic household wastes (e.g., food and garden) along with other organic fractions (e.g., paper, textiles, rubber, and wood). The potentially biodegradable fraction of MSW can vary widely from region to region, though a raw estimate of 45 % of MSW can be assumed for mixed waste (Worrell et al., 2017). Likewise, a biogas yield ranging from 150 to 200 Nm^3 per ton of fresh matter has been reported for biowaste (Rohstoffe eV, 2020). Assuming 60 % of methane content in biogas, the amount of fuel energy converted to electricity in typical internal combustion engines rises from 28 % in small units up to 43 % for large engines (Rohstoffe eV, 2020).

The generation potential from the incineration of MSW proved to be three times greater than that from anaerobic biodigestion (Table 4), mainly because only a small fraction of MSW can be treated by the AD without energy recovery from the digestate. However, incineration has technological requirements to be met. Before incineration, the waste must be dried, and if the LHV is between 4.2 MJ/kg and 7.1 MJ/kg, these must be mixed with other auxiliary fuels (Kumar and Samadder, 2017). The steam parameters of the boiler should not exceed 420 °C and 400 kPa to avoid excessive corrosion caused by acid gases and other compounds produced by MSW, limiting the achievable electrical efficiency. However, it is possible to increase the electrical efficiency beyond 30 % by using steam cycles with superheating and an advanced protection system against corrosion (Reddy, 2019).

Table 4. Theoretical energy potential of MSW

Biomass	Amount 2019 (t)	Thermal energy potential (GWh)	Electricity gross potential (GWh)	Electricity net potential (GWh)
MSW. Incineration	4 676 600	10 135	2 654	2 256 [a]
MSW. Anaerobic digestion	2 239 400	2 118	847	657 [b]

Considering the electrical self-consumption as in [a)] (Lorenzo Llanes and Kalogirou, 2019) [b)] (Worrell et al., 2017)

Another problem to be faced in incineration plants is fly ash. Fly ash, which constitutes 2-3 % of the total mass of MSW incinerated, is a dangerous pollutant and must be treated as such (Kalogirou, 2017). The treatment of the ashes can be solved by another thermochemical process for instance plasma gasification, this process also allows to obtain useful energy from various fuels including hazardous wastes and wet materials. Plasma gasification technologies are still immature and their high costs do not make them competitive for the current Cuban situation; however, it should be studied further as it proposes a zero waste solution (Tamayo Pacheco et al., 2020).

On the other hand, AD is an attractive and sustainable process for treating MSW since it generates energy and a digestate that can be used as fertilizer (Giuliano et al., 2020). Although AD is a well-established technology, it presents challenges such as starting the reactors and the demanding separation of the inorganic fraction as an essential requirement. Other than technologies, transportation distance has been suggested as the main factor affecting the sustainability of AD (van Fan et al., 2018).

Other biomasses. Rice husk, forest biomass and livestock residues

Agricultural and forestry residues in Cuba are diverse, but they are scattered, so that the potential of two with greater availability, rice husk and forest residues, will be evaluated. Rice husk can be used to meet the heat and electricity demand in the rice milling industry, and to produce surplus electricity. In the case of forest biomass, the main objective is its use to produce electricity for self-consumption and exportation to the grid. The energy potential was assessed based on previous results from Colectivo de autores CUBAENERGÍA (2018), which were updated according to the 2019 rice production. In both cases (i.e., rice husk and forest residues), combustion integrated into a steam boiler were considered as technology for the assessment (Table 5).

Table 5. Indices for calculating the energy potential of rice husks and forest residues

Technology	Assumptions	Units	Value	Reference
Rice husk combustion + steam boiler	Mass ratio husk/ rice	%	19.4	(Colectivo de autores CUBAENERGÍA, 2018)
	LHVw.b.	MJ/kg	14.2	idem
	Rice production (2017)	t	404 733	(ONEI., 2020)
	Rice husk mass (2017)	t	78 420	(Colectivo de autores CUBAENERGÍA, 2018)
	Estimated Gross electricity	MWh	34 379	idem
	Rice production (2019)	t	391 842	(ONEI. 2020)
Forest biomass combustion + steam boiler	Electricity Index	kWh/kg	0.62	(Colectivo de autores CUBAENERGÍA 2018)

In the case of organic livestock waste, the calculation procedure and results of the 2017 case study published in Colectivo de autores CUBAENERGÍA (2018) were taken into account (Table 6). It is proposed to update the calculations according to the number of heads of cattle, pigs and poultry in 2019. As in Colectivo de autores CUBAENERGÍA (2018), it was considered that only 20 % of the cattle manure could be collected by the way they are raised. As an electricity generation scheme, anaerobic digestion integrated with an internal combustion engine is proposed.

Table 6. Indices for calculating the energy potential of livestock waste

Technology	Assumptions	Units	Value	Reference
Livestock residues AD + ICE	Pig heads (2017)	10^3	2 069	(ONEI., 2020)
	Cattle heads (2017)	10^3	3 865	idem
	Poultry cattle heads (2017)	10^3	13 886	idem
	Biogas generation (2017)	NM^3	34 379	(Colectivo de autores

				CUBAENERGÍA 2018)
	LHVw.b. biogas	MJ/kg	23	idem
	Estimated Gross electricity	MWh	245 760	idem
	Pig heads (2019)	10^3	2 676	(ONEI., 2020)
	Cattle heads (2019)	10^3	3 817	idem
	Poultry cattle heads (2019)	10^3	12 253	idem

Table 7 shows the calculated potentials for each biomass (i.e., rice husk, forest residues, and livestock waste). The results show, that livestock waste has the highest potential of these three biomasses. The theoretical energy potential from biogas was also calculated in Suárez-Hernández et al. (2018) with different results than those proposed in Colectivo de autores CUBAENERGÍA (2018). In the former, an annual biogas production of 246 *M*m^3, including industrial wastes (food and distilleries), led to an estimate of 1 477 GWh thermal. Also, the estimated biogas generation from cattle and pig manures was higher. An aspect that was not addressed in either of the two cited publications is the co-digestion of complementary substrates in the same reactor, thereby balancing the composition of the substrate, including the C/N ratio to promote an increase in biogas production (Colla et al., 2019).

The assumptions in Tables 5 and 6 correspond to current production situations in Cuba, but the aspirations focused on to food self-sufficiency of Cuban society are greater. For example, if all the rice that the country needs for self-consumption were produced (700 000 t of wet rice), the rice husk and its energy potential would increase more than three times.

Table 7. Theoretical energy potential of rice husks, forest residues and livestock waste

Biomass	Amount 2019	Unit	Thermal energy potential (GWh)	Electricity gross potential (GWh)	Electricity net potential (GWh)
Rice husk	75 922	t	302	33	16*
Forest residues	235 724	t	805	146	125*
Livestock waste	146 209 771	m^3	937	263	92*

* Considering the electrical self-sufficiency as in Colectivo de autores CUBAENERGÍA (2018)

Nevertheless, the theoretical potential of livestock waste cannot be exploited in reality. Factors such as the waste volumes from the farms limit the size of the biogas plants; thus, their economic feasibility. On the other hand, the remoteness of the farms to electricity consumers and the decrease in electrical efficiency in smaller plants also reduce the economic performance of any potential project. Hence, further studies focusing on the effectiveness of centralized versus decentralized systems are needed. Likewise, a better understanding of synergies between plant capacities, biomass supply chain, and integration to the electrical grid will support the final decision-making. According to a recent study, biogas can contribute to 7 – 10 % of electricity in Cuba. To this end, the introduction of biogas technology in production plants that generate large amounts of wastewater or where the waste generated by various production systems can be collected is needed (Romero-Romero, Caraballoso-Granado, and Hartmann, 2020).

Once the theoretical potentials of the different biomasses were calculated, it was shown that the total potential is in the range of 34 491- 36 298 GWh according to the variant that is selected for the energy use of the MSW. This represents 115 – 121 % of the electricity generation planned by the government for 2030.

Current situation

The current situation of bioenergy in Cuba in the first five years of the last decade grew, but in the latter five years, the trend has been decreasing (See figure 1) despite the will of the stakeholder involved in its development. The sugar industry continues to be by far the main self-producer of electricity from biomass. In the 2018 and 2019 harvests, the milling did not exceed 50 % of the planned, leading to a negative energy balance. The electricity self-supply reported nationwide in these harvests was 94.2 % and 93.6 %. In the 2019-2020 harvest, the positive balance was recovered at the national level, with 102 % self-sufficiency. In this sense, the objective is to achieve self-sufficiency of 115 % and thereby export to the network (Extremera San Martin and Guerra de Silvestrelli Delgado, 2021).

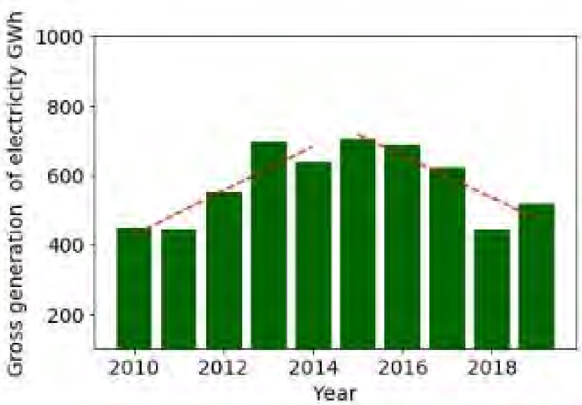

Figure 1. *Annual electricity production in the sugar industry in Cuba*

The electricity production in the sugar industry is well below its potential. In 2017, the gross generation of electricity was 622 GWh. This result is a consequence of the insufficient harvested area (Harv. area), the low cane yield by area (Yield), and the low electricity generated per ton of cane processed (E. gen.), as can be observed in Figure 2. The E. gen. is the index that more affects the electricity production and it is related to the low efficiencies in the steam cycles and shortcomings in sugar milling. The real harvested area was 44 % of the theoretical amount and only 34 % of the approved land for cane production, equivalent to 934 000 ha.

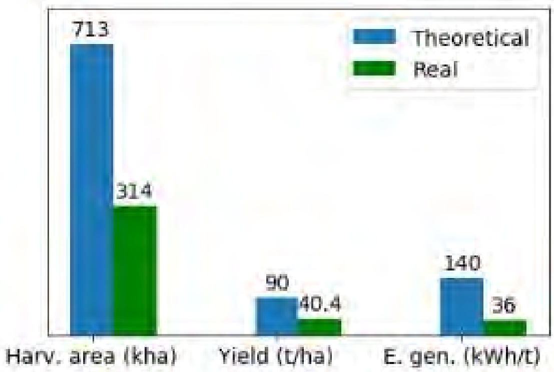

Figure 2. *Comparison of theoretical and real indices (2016-2017 harvest). Harvested area (Harv.area), cane yield, and electricity generated per ton of cane processed (E.gen).*

Another element to be considered is that the installed capacity in the sugar mills is not enough to fulfil the theoretical plan, therefore new capacities are needed. In this sense, the first biomass-fired power plant (which in Cuba is called "bioeléctrica") was built and is currently in operation in the start-up phase.

Regarding biogas technology, the first biogas industrial plant was set up in 2017 in a pig farm called Frank País, in Matanzas province. It has a volume of 1 853 m^3, a diary biogas production of 771 m^3, and a diary electric generation of 1 542 kWh. On the other hand, gasification technology for electricity generation also has few facilities (5) in Cuba. The largest is located in La Melvis at Isla de la Juventud with a generation capacity of 500 kWe from forest biomass. It is followed in size by two located in Cocodrilo at Isla de la Juventud and in La Veguera at Camaguey, both capable of generating 50 kWe from forest residues and marabu respectively. The other two are located in El Brujo (sawmill waste) in Santiago de Cuba and in the Indio Hatuey experimental station (various biomasses) in Matanzas with 40 kWe and 22 kWe respectively (Sánchez-Hervás et al., 2018).

Future perspectives

The generation in the sugar mills is decisive to increase the participation of renewable sources in the Cuban energy matrix. Since 2016, the perspectives of energy use in the sector were studied to establish the realistic potentials until 2030. For this, technical and economic aspects were taken into account (Rubio González and Rubio Rodríguez, 2019). Based on this study, the Cuban program for the maximum use of sugarcane biomass for electricity generation was established.

This program considers the addition of cane straw and its mixture with bagasse as primary energy sources, and its complement with forest biomass in season outside the harvest. It includes the expansion of milling capacities, covers 54 of the 56 sugar mills in the country, and proposes new high-efficiency thermal plants. In this study, the number of biomass-fired power plants to be built was concluded, as well as the tributary mills that will sell the bagasse. Also, the boilers' steam parameters, the technological schemes to be used, and the biomass-fired power plants optimization were addressed.

As a result of this study, it was established a plan for the creation of 25 biomass-fired power plants with 14 tributary sugar mills. It was shown that biomass-fired power plants projects are unfeasible for sugar mills with 4 000 t/day or less milling capacities. The plan recommends an average of 143 days harvest time, an installed capacity of 1 070 MW (870 MW in new power plants), allowing a total gross generation of 4 262 GWh per year, of which 3 209 GWh are contributed to the national electricity grid. These numbers lead to a generation index of 116 kWh/t and guarantee 14% of participation in the total generation of the country (Rubio González and Rubio Rodríguez, 2019).
Taking this plan into account, the Ministry of Agriculture in Cuba carried out an analysis of the availability of forest biomass in areas adjacent to the possible locations of the bioelectric plants, which yielded a demand for forest biomass of 2.3 Mt per year, for which 15 kha must be harvested per year (GAF, 2019). This study indicated that only seventeen of the 25 bioelectric plants evaluated have marabu reserves to give them a number of years of operation that justify the investment in harvesting and logistics systems. Consequently, it has been proposed to reduce the plan to 17 new biomass-fired power plants, mainly because there is no land available in some areas to promote energy forests.

Challenges of the energy use of biomass in Cuba

There are many challenges to face to increase the energy use of organic materials in Cuba. The primary challenge is the economic-financial one to carry out the new investments and modernizations. The solution is to search for investors or do it with their capital, apply to development funds and international projects. In this sense, the portfolio of opportunities of the plan for foreign investment foresees the installation of 755 MW through 19 biomass-fired power plants adjacent to sugar plants, to operate for more than 200 days a year with sugar cane and forest biomass available in areas close to these plants (Ministerio de Comercio Exterior e Inversión Extrajera [MINCEX], 2019). To do that an investment cost of 2 500 dollars per kW of installed power is estimated. These biomass-fired power plants will produce more than 1 900 GWh/year. The ministry of foreign trade is promoting three business opportunities for the administration of biomass-fired bioelectric plants, as well as the modernization of the Héctor Molina sugar mill (Ministerio de Comercio Exterior e Inversión Extrajera [MINCEX], 2019).
Other business opportunities are the integral management of solid waste and power generation in the Mariel Special Development Zone and Artemisa province, including constructing a power generation and processing plant. To do that an investment of more than 15 million dollars is planned (Ministerio de Comercio Exterior e Inversión Extrajera [MINCEX], 2019).
Regarding the technological challenges, those related to the use of biomass for electricity generation with steam boilers stand out, which implies the burning of biomass for the generation of steam and its use in turbines. Achieving high efficiencies in this cycle entails raising the steam parameters as much as possible, which causes the metals in the superheaters to operate at very high temperatures. At high temperatures, the corrosion and scale phenomena are significantly accelerated. Corrosion and scale are due to the presence of alkalis (especially potassium) and chlorine in the biomass (Rubio González and Rubio Rodríguez, 2019).

In the first biomass-fired power plants, the temperature of the superheated steam was limited to 450 °C, as a result of experience with the use of various fuels. At 450 °C, the corrosion rate is small and follows a parabolic law, but at 650 °C, the rate increases and has an almost linear relation (Berlanga-Labari and Fernández-Carrasquilla, 2006). The phenomenon described is present when forest biomass (including marabu) and sugarcane agricultural residues (SCAR or cane straw) are burned. In the case of bagasse, the situation is different, since it is obtained from the milling and washing of the cane (leaching) that dilutes a good part of the dangerous substances.

At present, to face corrosion problems and to be able to raise the cycle parameters, there are different alternatives (Rubio-González et al., 2021). The most used are co-combustion with less problematic fuels (bagasse), protective coatings in superheaters and burning in fluidized bed furnaces, dry cleaning, leaching or the use of chemical additives.

Other challenges in the use of biomass are: adequate logistics (collection, transport and storage) given its low energy density, physical pretreatment to adapt its granulometry and humidity to achieve efficient combustion, and the selection of the suitable oven taking into account variations in humidity and ash content.

Conclusions

The yearly theoretical energy potential of the biomass in Cuba is between 34 491- 36 298 GWh. The two most abundant resources are the by-products of the sugar industry, the marabu and the MSW. The energy potential of the sugar industry by-products and marabu or energy cane must be understood as one concept because it guarantees the maximum use of the installed capacities. The energy potential of the sugar industry by-products and marabu represents 91-96% of the total theoretical energy potential depending on the selected technology for MSW treatment. Then, applying the Pareto principle, most efforts should be focused on the development of biomass-fired power plants to increase the participation of biomass in the Cuban energy matrix.

The generation of electricity from biomass in Cuba has had, in the last 10 years, initially increasing and then decreasing behaviour. A turning point in this last tendency is expected from the start-up of the first biomass fired power plant and the compliance with the Cuban program for the maximum use of sugarcane biomass for electricity generation. In addition to the new capacities installed, an increase in harvested area, cane yield, and electricity generated per tons of cane processed are essential.

The above results correspond to a theoretical study. More research is needed to establish the technical and economic potentials, also taking into account the geographical distribution of biomass resources and the conditions of the electrical network. Other topics as the characterization of the MSW in each geographic zone and the identification of the higher biomass sources should be studied to create new capacities and new profitable energetic business opportunities.

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IV. 5. The role of hydropower in the Cuban electricity system and future plans towards 2030

Leonardo Peña Pupo, Ernesto Yoel Fariñas Wong and Angel Luis Brito Sauvanell

Introduction

Cuba is a Caribbean country. Approximately a quarter of the territory is mountainous with hills dotted across the island, alternating with plains, and three main mountain ranges: The Nipe-Sagua-Baracoa and the Maestra in the north-east and south-east (Figure 1), the Guamuhaya in the centre (also known as mountains of the Escambray) and the Guaniguanico in the west. The Maestra is the largest mountain range and home to “Pico Real del Turquino”, the country’s highest peak at 1.974 metres. The topography and climate of the island result in short rivers with reduced flows. The longest river is the Cauto, at 249 km, flowing westwards north of the Maestra. Other major rivers include the Sagua la Grande, Zaza, Caonao and San Pedro. The Toa River (116,2 km), located in the provinces of Holguín and Guantanamo, has the largest volume of flow in the country (Peña Pupo and Fariñas Wong, 2021).

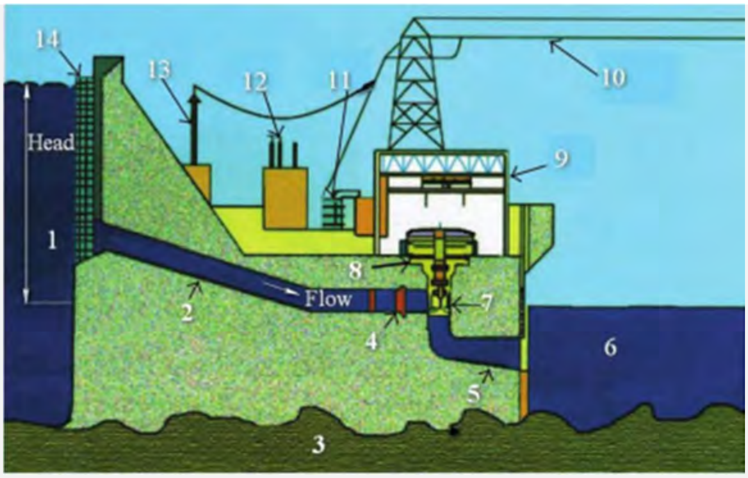
Figure 1. *Cuba island and main mountains range. Adapted from* www.mapamundi.online/wp-content/uploads/2019/02/mapa-fsico-cuba.jpg

Cuba has more than one hundred years of experience in the use of hydropower for electricity generation, being one of the most utilized renewable energy technologies in the first half of the 20th century. Due to Cuba’s short rivers with reduced flows, it cannot build large hydropower plants for electricity generation. However, Cuba has identified considerable potential in the construction of small and micro hydropower plants in certain mountains locations. Currently, hydropower is the third renewable source in Cuba with a total installed capacity of 68 MW (Peña Pupo and Fariñas Wong, 2021).

To increase further the role of hydropower in the energy mix of the country, a program for the construction of 74 small hydroelectric plants with more than 56 MW of capacity has been elaborated using the dams already built in the country and the water available in water channels and water mirrors. The construction of pumped hydropower plants (PHP) is another field where Cuba has identified a potential for energy development. According to the electricity necessities and topographical conditions of the island, the Cuban government has carried out studies for the construction of PHP to better integrate PV and wind power renewable energy and to reach the goal of 24% in renewable energy towards 2030 (Ministerio de Comercio Exterior e Inversión Extrajera [MINCEX], 2019).

Technically speaking, hydropower is the rate at which hydraulic energy is extracted from a specific amount of falling water as a result of its position or velocity or both. The rate of change of angular momentum of falling water or its pressure or both on the turbine blade surfaces creates a differential force on the turbine runner thereby causing rotary motion (de Souza, Moreira, and da Costa, 2018). As a working fluid, water in a hydropower system is used instead of consumed, it is thus available for other uses like irrigation or supply to people (Peña Pupo, Gutiérrez Urdaneta, and Hidalgo González, 2016).

The basic schematic diagram for hydropower and its main components is shown in Figure 2. To produce electricity, the hydraulic turbine output shaft is coupled to the electric generator. A typical Synchronous generator is principally made up of an electromagnetic rotor that is located inside the stator containing a winding of electric wires. During operation, the rotor in the stator turns and generates electricity by the principle of electromagnetic induction. The generated electricity is transmitted to the electric grid or users, in isolated operations, through a transmission system that consists of components such as switchyard or sub-station, transformers, and transmission lines.



(1) Reservoir
(2) Penstock
(3) Bedrock
(4) Valve
(5) Draft tube
(6) Tailrace water
(7) Turbine
(8) Generator
(9) Powerhouse
(10) Transmission lines
(11) Transformer
(12) Insulators
(13) Transmission tower
(14) Trash rack

Figure 2. *Schematic view of the typical Hydropower plant and its main components.*
Adapted from Kaunda, Kimambo, and Nielsen (2012)

Generally, two types of turbines are used: impulse turbine for instance Pelton Wheel turbine and reaction turbine-like Francis and Kaplan turbine. The power available is proportional to the product of the pressure head and volume flow rate. The general formula for any hydro system's power output is:

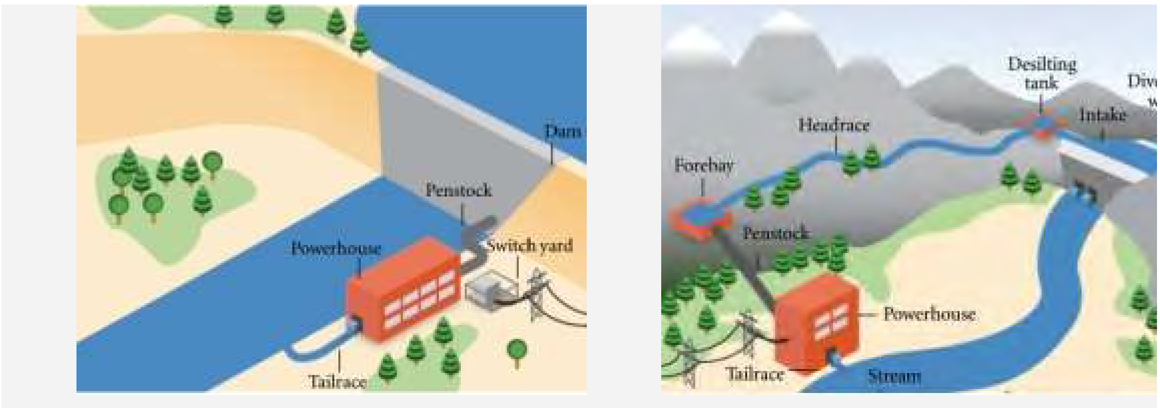
$$P = \rho * g * Q * H * \eta \qquad [W] \qquad (1).$$

where P is the mechanical power produced at the turbine shaft (Watts), η is the hydraulic efficiency of the turbine, ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), Q is the volume flow rate passing through the turbine (m^3/s), and H is the effective pressure head of water across the turbine (m). The best turbines can have hydraulic efficiencies in the range of 80 to over 90 per cent (higher than most other prime movers), although this will reduce with size. Micro-hydro systems tend to be in the range of 60 to 80 per cent efficient.

The selection of the best turbine for any particular hydro site depends upon the site characteristics, the dominant ones being the head and flow available. The selection also depends on the desired running speed of the generator or other devices loading the turbine. Other considerations, such as whether the turbine will be expected to produce power under reduced flow conditions, also play an important role in the selection. All turbines have a power-speed characteristic and an efficiency-speed characteristic. They will tend to run most efficiently at a particular speed, head and flow.

Hydropower Plants Classification

Hydropower plants generally differ from their turbine installed capacity, water heads, technologies, storage capacity, installation sites, and specific applications. When categorizing hydropower basin on levels of water impoundment, there are three main types of projects namely: run-of-river, reservoir (storage hydro) and pumped storage.



a) b)

Figure 3. *Schematic diagrams of typical hydropower plants: a) reservoir, and b) run-of-river* (Kaunda et al., 2012).

A storage hydropower project is schematically illustrated in Figure 3.a). A reservoir is usually installed behind a dam to store water for later power generation and other purposes (such as irrigation and water supply). Storage hydropower schemes are typically used for river systems of highly fluctuated flows. The water flow can be regulated by the reservoir. Besides, storage hydropower projects can regulate flow in the river downstream of the dam. Further, because the flow into the powerhouse can be regulated, the performance of power control and the overall energy conversion efficiency is thus enhanced for a storage hydropower system. Some flow-sensitive turbines like Kaplan and Francis are able to be operated at the best efficiency point. Generally, in Cuba, most of the grid-connected Hydropower plants are storage plants, although “El Guaso” 1.050 kW is a run-of-river.

Run-of-River (RoR) Hydropower plants generate electricity from the river flow without significant storage. RoR scheme is more suitable for a river that has small flow variations or a river that is regulated by a large natural reservoir. It consists of these main components as schematically shown in Figure 3.b). RoR projects do not require large construction activities, which bring significant economic benefits. RoR projects impose fewer environmental problems because they use the natural flow of the river, and a relatively little change happens in the stream channel and flow. Because of their economic and environmental advantages, RoR schemes are commonly used in small-scale hydropower systems. All grid-isolated Cuban Hydro are RoR, they use Pelton turbines because of their high efficiency under low flow and high head conditions.

Pumped-Storage Plant (PSP) has been the most important large-form storage mechanism in power systems (Vasudevan et al., 2021) The water is pumped from a lower reservoir into an upper reservoir during off-peak hours, the extra electricity is transformed in the form of potential energy in the water of the upper reservoir (see Figure 4); In contrary, a large amount of electricity is demanded during the peak-loads times, the reversible pumped-turbines work at the generation mode. The water stored in the upper reservoir is hence released back to the lower reservoir. In Cuba, they have been studied around 30 places with very good hydrological, geologic and topographical conditions for the PSP construction, located in the three geopolitical regions of the country: east, centre, and west (Peña Pupo and Hidalgo, 2019).

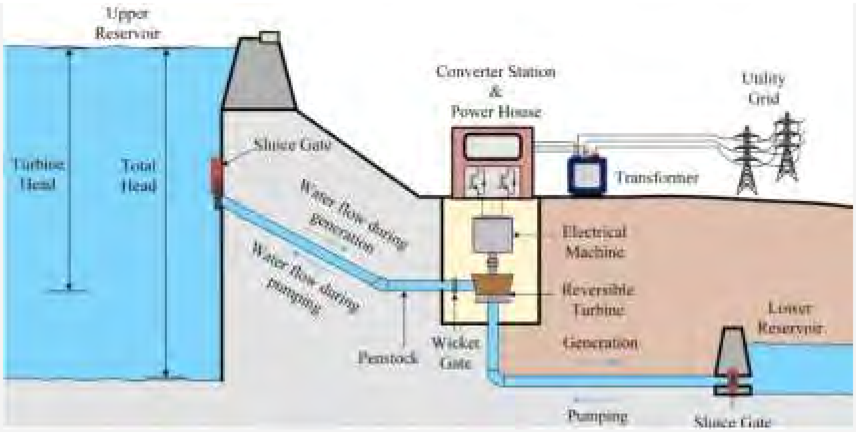


Figure 4. *Schematic diagram of a PSP* (Vasudevan et al., 2021).

Hydropower plants also can be classified according to their installed electricity capacity (size). International consent is not reported for the classification of the power stations according to their installed power. Table 1 shows the classification of Hydropower plants for different countries and regions, where it is verified that: for the same region, is differences regarding what value it is considered mini or micro Hydropower plant.

Table 1. Hydropower Classifications by Installed Capacity (Peña Pupo, 2020).

Institution	Micro (kW)	Mini (kW)	Small (MW)	Large (MW)	Region
OLADE*	5-50	51-500	0,5-5	> 5	Latin america
HRC*	5-50	51-500	0,5-10	> 10	China
IDEA*	0-50		0,5-10	> 25	Spain
ESHA*	< 500	-	< 10	-	Europe
ITDG*	0,2-300	300-10000	-	-	Peru

**HRC: Hangzhou Regional Center; IDEA*: Institute of Diversification and Energy Saving; ESHA*: European Small Hydropower Association; ITDG*: Intermediate Technology Development Group.*

In Cuba is applied the terminology of the Latin American Organization of Energy (OLADE) although some Latin American authors don't agree with this classification (Peña Pupo, 2020) and they refer to them indistinctly. In many countries, especially in Europe, a limit of 10 MW is usually defined to classify the small-versus large-scale HPP. Further, the small HPP (SHP) can be categorized into Pico, Micro, and Mini scheme (Guo, 2019). China classified SHP with an installed capacity of less than 10 MW (Peña Pupo and Fariñas Wong, 2021).

Another classification of HPP is based on the water level difference between the inlet and the outlet, that is, the water head and the definition is also not identical. In practice, the water head is a significant factor to select the appropriate hydraulic turbine (Gutiérrez Urdaneta, Peña Pupo, and Hidalgo González, 2019). Depending on the height of the water heads, Hydropower plants can be classified into three categories according to the European Small Hydropower Association (Guo, 2019) as follow: 1) High head if the head is 100 m and more; 2) Medium head: for heads about 30 m to 100 m; and 3) Low head for heads about 2 m to 30 m. Except for Hanabanilla HPP with 240 m of hydraulic head, all the Cuban HPP reservoirs classify as low head. However, the grid-isolated Cuban SHP classify as the high hydraulic head.

Because HPPs are able to respond to power demand fluctuations much faster than thermal electric power stations, Hanabanilla 43 MW HPP plays an essential role in the Cuban electric system making secondary frequency regulation. Its location in the centre of the island (Figure 1. Zone 2) makes it allow to carry out its capacity of secondary frequency regulation in a better way. Cuban HPP is a flexible energy conversion technology and also explains why reservoir grid-connected HPPs are used for peaking purposes.

Model of a hydropower Pelton turbine

Cuban electricity sector overview

In 2020, installed capacity in Cuba totalled 6.660,5 MW, with approximately 46 per cent from thermal power plants, including 8 per cent from generators operated by the Ministry of Energy and Mines and the Group of Sugar Industries (AZCUBA). Grid-connected internal combustion (IC) power generators contributed 41 per cent, 9 per cent was from gas turbines and 3 per cent from solar photovoltaics (PV) and wind power energy. Only 1 per cent of installed capacity was from hydropower (Figure 5) (ONEI, 2021).

Figure 5. *Installed electricity capacity by source in Cuba (MW), Source: (ONEI, 2021)*

In 2020, annual electricity generation in Cuba was approximately 20.472 GWh (Figure 6). Fossil fuel-based thermal power plants contributed approximately 72 per cent, including gas-powered turbines and other thermal power plants from industries (mainly biomass from the sugar cane industry). IC generators contributed 26 per cent, while hydropower and other renewable energy sources (including wind and solar power) contributed 2 per cent combined. Total renewable electricity in 2020 amounted to 919,6 GWh (4,5 per cent), including 546,9 GWh of biomass (ONEI, 2021).

Figure 6. *Annual electricity generation by source in Cuba (GWh)* (ONEI, 2021).

According to ONEI (2020), Cuba achieved a 100 per cent electrification rate in 2018, meanwhile, recent official updates ONEI (2021) refers to 99,98 per cent to 2020. There is no official information about this "little" (0,02) per cent of difference, but it seems due to some displacements of some families in rural areas. Total electricity consumption reached 17.045,7 GWh in 2020 (losses of 3.426,8 GWh), with the residential and public sectors having consumed approximately 45 and 38 per cent, respectively**.** The gross generation index stood at 1,8 MWh per citizen. Losses amounted to approximately 17 per cent (ONEI, 2021).

According to Cuba's Information and Statistical National Office (ONEI), the electricity sector in Cuba is fully public (ONEI, 2021) owned by the Electric Union of Cuba (UNE). UNE is part of the Ministry of Energy and Mines (MINEM) and is the main entity responsible for the generation, transmission and distribution of electricity in the country, with the exception of the electricity generated by sugar cane biomass, which is owned by AZCUBA. On the other hand, the National Institute for Hydraulic Resources (INRH) is the regulatory authority responsible for the management of water resources. However, hydropower plants are owned by UNE and water use for hydropower generation is subordinated to irrigation and population supply. Furthermore, Cuban's reservoirs are not built exclusively for electricity production (Gutiérrez Urdaneta et al., 2019; Ministerio de Justicia (MINJUS), 2017; Peña Pupo and Fariñas Wong, 2020). From the Cuban hydropower operation point of view, this is the most distinctive sector characteristic.

Cuban Hydropower sector description

The current installed operational hydropower capacity in Cuba is 68 MW, with 43 MW from the Hanabanilla HPP and 25 MW from Small Hydropower Plants (SHP), in accordance with the up to 10 MW definition (Liu et al., 2019). The installed capacity has oscillated, as it is shown in Figure 7, mainly due to decommissioning for technology ageing and new investments but in a lesser role (ONEI, 2021; Peña Pupo and Fariñas Wong, 2021; UNE and EMFRE, 2020).

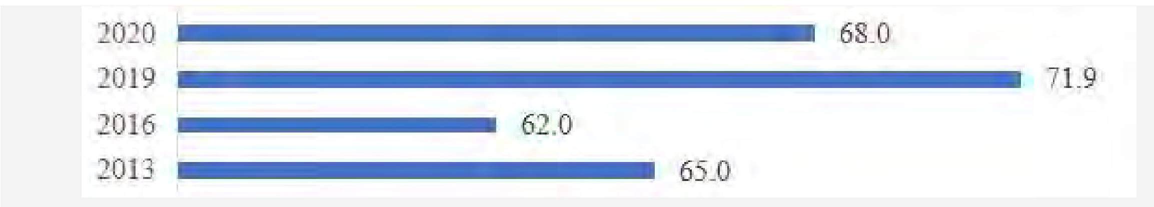


Figure 7. *Installed capacity from 2013 to 2020 (MW).*

There were a total of 170 hydropower plants in Cuba. Of these, 138 were operational SHP plants, including 41 SHP plants connected to the SEN and 97 SHP plants (70 per cent) operating in isolation from the SEN (UNE, & EMFRE, 2020), offering service to 8,486 isolated households with 33.944 inhabitants (del Campo, 2020; Ministerio de Energía y Minas (MINEM), 2020). Currently, 32 SHP plants are identified as non-operational, of which 25 plants lack water supply as a result of climate change and 7 SHP need refurbishment (Peña Pupo and Fariñas Wong, 2021). Table 2, show a full list of Cuban HPP by province.

Table 2. Cuban operational HPPs by province and Power Capacity (UNE and EMFRE, 2020).

PROVINCE	Micro (unit)	Power (kW)	Mini (unit)	Power (kW)	SHP (unit)	Power (MW)	HPP (unit)	Power (MW)
Pinar del Río	6	121,0	1	270,0	0	-	0	-
Artemisa	3	90,0	0	-	0	-	0	-
Villa Clara	3	90,0	4	640,0	0	-	1	43,0
Cienfuegos	9	218,4	5	765,0	1	1,6	0	-
Sancti Spíritus	3	84,0	0	-	1	2,7	0	-
Ciego de Ávila	0	-	0	-	1	1,04	0	-
Granma	21	455,2	3	274,0	3	5,21	0	-
Holguín	4	88,0	0	-	2	4,8	0	-
S. de Cuba	18	425,0	6	951,0	1	1,53	0	-
Guantánamo	36	744,0	4	541,0	2	2,3	0	-
TOTAL	**103**	**2.315,6**	**23**	**3.441,0**	**11**	**19,226**	**1**	**43,0**

The biggest quantity of HPPs is located in the east area of Cuba island (see Table 2.): from Granma to Santiago from Cuba provinces. However, the biggest installed power capacity is in the centre of the country (Villa Clara). This is due to the Hanabanilla 43 MW HPP. Some of the east HPPs are isolated from electric systems, in mountain communities. These HPPs are very important to accomplish rural development and generally are mini or micro hydropower plants. In the east of the country are too the major quantities of the most grid-connected productive SHP.

The ten most productive HHP plants in Cuba are listed in Table 3. Given some SHP plants were commissioned decades ago, they require refurbishment. For budgetary reasons, only the C. M Céspedes SHP was refurbished in 2019. Many of these power stations are open to proposals of foreign investment according to the Ministry of investment and foreign commerce (Ministerio de Comercio Exterior e Inversión Extrajera [MINCEX], 2019).

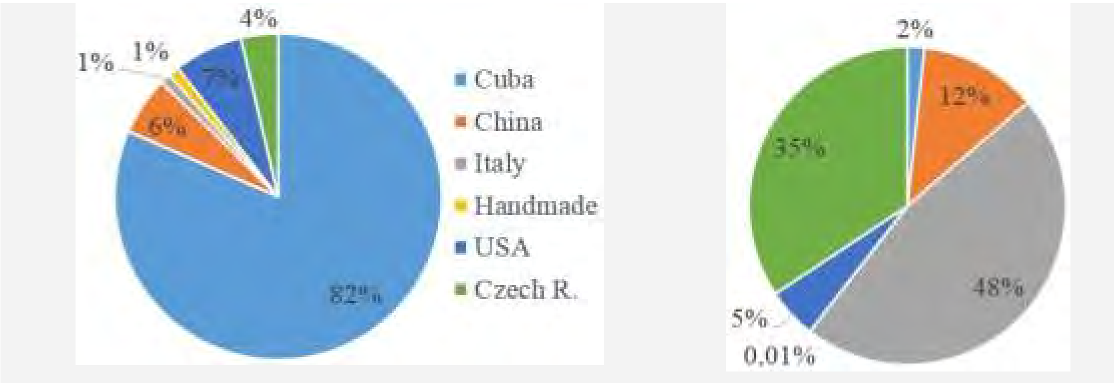
Table 3. Most productive operational SHP plants in Cuba (Peña Pupo and Fariñas Wong, 2021).

Name	*Province*	*Capacity (MW)*	*Head (m)*	*Plant type*	*Launch year*
Mayarí MD	Holguín	2,85	43	reservoir	2018
Bueycito	Granma	1,46	30	reservoir	2012
Nuevo Mundo	Holguín	2,00	44	reservoir	2010

Zaza	Sancti Spíritus	2,70	8	reservoir	2009
Corojo	Granma	2,00	33	reservoir	2003
Chambas	Ciego de Ávila	1,04	29	reservoir	2003
C. M de Céspedes	S. de Cuba	1,53	34	reservoir	1998
Yara	Granma	2,60	42	reservoir	1986
Hanabanilla	Villa Clara	43,0	240	reservoir	1968
El Guaso	Guantánamo	1,05	190	run-off-river	1917

Technologies and installed capacities from origin countries

Cuba imported several of these hydropower plants from China (Figure 8. a), b)). Cuba has manufactured the rest within the country but with the aid of the USSR and the Czech Republic, mainly. In the province of Villa Clara is the only one Cuban hydropower turbine factory, well-known as "Planta Mecánica". In this factory all the hydropower turbines of the type Pelton TP-15, TP-16 and 650x65 were manufactured, as well as those of crossed flow (Banki) B-30/35U, 15A3, and MB-2, among others (Pérez, 1983) Near to 90 per cent of the grid-isolated Cuban mini and micro-hydropower plants work with TP-16 Pelton turbines (Figure 8. a)) (Peña Pupo, 2020).



a) Technology by country's origin

b) Installed Capacity Power by country's origin

Figure 8. *Technologies and capacities from country's origin*

Italy and the Czech Republic historically, have exported most of the installed capacity of Cuba. This is a consequence of the three units of 43 MW Hanabanilla HPP, two turbines are Italian and the third are from Czech Republic (Figure 8. b)). However, currently, the biggest quantity of technology units, supplies and spare parts have been imported from China. The hydropower technology of the USA is in the 1,50 MW HPP "El Guaso", built-in 1917 and still in operation (Figure 8. a) and b)). Handmade technology (Hydraulic wheel) is present, to own supply in a mountain region in the east. Handmade technology (Hydraulic wheel) is present, in a mountain region one-home to self-supply (4 kW) in the east (Figure 8. a) and b)).

Current investment projects

Currently, there are two SHP plants foreseen to be completed in 2021: The Alacranes SHP (2,1 MW) in Villa Clara and the Mayarí left margin (MI) SHP (1,25 MW) in Holguín (Table 4). both with Chinese technology Furthermore, in 2020 a feasibility study of one pumped storage hydropower of 200 MW in Mayarí was completed (del Campo, 2020). Given that Cuba does not have major rivers or large bodies of inland water, the development of hydropower will remain focused on small-scale projects.

Table 4. Ongoing SHP projects in Cuba (Peña Pupo and Fariñas Wong, 2021).

Name	*Capacity (MW)*	*Head (m)*	*Planned launch year*	*Development stage*
Alacranes	2,1	13,0	2021	construction
Mayarí MI	1,25	13,5	2021	construction

Small hydropower projects from current investment

In 2016, Cuba signed an agreement with the Kuwait Fund for Arab Economic Development (KFAED), which provided US$ 30 million for the construction of 34 SHP projects with a combined capacity of 14,6 MW (International Hydropower Association (iha), 2019; Peña Pupo and Fariñas Wong, 2021) Table 5 provides a list of selected sites available for development or refurbishment based on full feasibility studies.

#	SHP	Province	Capacity (kW)	Generation (MWh)/ year
1	Canal Yara	Granma	250	1.134
2	La Felicidad	Sancti Spiritus	200	1.540
3	La Paila	Artemisa	750	3.933
4	Protesta de Baraguá	Santiago de Cuba	1.200	4.761
5	Cauto el Paso II	Granma	700	2.910
6	Guaso	Guantánamo	2.000	7.500
7	Jimaguayú	Camagüey	800	3.612
8	Los Palacios	Pinar del Río	640	3.380
9	Guayabo	Holguín	800	4.800
10	Guisa	Granma	250	1.100
11	Najasa II	Camagüey	500	2.000
12	Guane	Pinar del Río	55	396
13	Canal Zaza	Sancti Spiritus	500	2.200
14	Céspedes 2da unidad	Santiago de Cuba	200	1.296
15	Cauto el Paso I	Granma	650	2.770
16	Lebrije	Sancti Spiritus	250	1.250
17	Juventud	Pinar del Río	800	4.147
18	Cidra	Matanzas	200	970
19	Paso Viejo	Pinar del Río	130	700
20	Guamá	Pinar del Río	160	990
21	Voladora	Cienfuegos	150	700
22	Avilés	Cienfuegos	250	1.491
23	Cautillo	Granma	750	3.185
24	Jaibo	Guantánamo	150	1.300
25	Tuinicú	Sancti Spiritus	320	1.872
26	Máximo	Camagüey	300	1.100
27	Bacunagua	Pinar del Río	300	1.600
28	Dignorah	Villa Clara	100	650
29	El Rancho	Pinar del Río	130	730
30	Najasa I	Camagüey	250	1.688
31	Muñoz	Camagüey	300	1.800
32	Palma Sola	Villa Clara	250	1.550
33	El Salto	Pinar del Río	180	990
34	San Pedro	Camagüey	150	740
	SUBTOTAL		**14.615**	**70.785**

Table 5. Ongoing SHP projects in Cuba by KFAED loan.

The project is known as the Construction of 34 Small Hydropower Plants (SHP) in Cuba. An increase of 14,6 MW power generation, has the following objectives: 1). To take advantage of existing reservoirs to generate electric power, contributing to reducing the environmental contamination. 2). To reduce the import of fossil fuel, obtaining significant economic savings. 3). To extend and improve electric services to people and other social facilities, mainly in rural areas. 4). To contribute to slow down the exodus of rural population towards cities and to boost the local production of food. And 5). To strengthen the capacity of universities and other research institutions, since the study of hydro technologies is addressed to the formation and updating of actual and future workers in hydropower plants.

The project aims to purchase technological equipment: turbines, generators, transport equipment, auxiliary equipment, etc. Also, purchase of building materials, fuel, tools, spare parts, etc., co-projection and technical assistance. Building, assembly and start-up of SHPs. Furthermore, by October 2020, some contracts had been signed with a European supplier (STM Power) for the development of 10 SHP projects and supply of SHP technology. The duration of the project is seven years, to 2022 (International Hydropower Association (iha), 2019; Ministerio de Energía y Minas (MINEM), 2020).

Identified Cuban Hydropower Potential

The technical potential of hydropower in Cuba is estimated, based on preliminary studies, to be 135 MW, including 13,7 MW in channels (Liu et al., 2019). This potential was determined by an inventory of potential sites in the 1980s. The study involved cartographic maps and precipitation measurements, with a few cases where a deep hydrological assessment was carried out. Currently, the estimated installed capacity of some SHP sites is being increased using hydrology assessment based on field investigations. However, the methods used were developed in Cuba in the 1980s. Thus, the current hydrological design remains weak due to the lack of local expertise in SHP.

The Government of Cuba drew up plans in 2016 for the development of 74 SHP plants by 2030, representing over 56 MW in capacity (274 GWh), which are available for foreign investment (Ministerio de Comercio Exterior e Inversión Extrajera [MINCEX], 2019). This would nearly double the country's current hydropower capacity, producing an estimated 274 GWh of renewable electricity annually and offsetting up to 230.000 tonnes of CO_2 emissions (Peña Pupo and Fariñas Wong, 2021). The updated estimate of potential SHP in Cuba is 81 MW, based on previous calculations of 56 MW of total planned capacity and the current installed capacity.

According to official investment information (del Campo, 2020), there is a lot of work to do on hydropower potential, but some identified items are listed in Table 6. The barriers that have limited the use of SHP in Cuba are similar to those that have limited the development of other renewable energy sources in the country. These technical and financial barriers include a lack of advanced technologies to further study hydropower potential, and limited financial resources (Liu et al., 2019; Peña Pupo and Fariñas Wong, 2021).

Table 6. Foreseen investments in Cuban HPP. Adapted from del Campo (2020)

Investment type	Quantity	Power (kW)	Energy (MWh)
Investment to do in built dams	68	32.368,0	121.372,1
Investment to do in not-built dams	3	10.000	58.360
Investment to do in water channels	5	13.720	94.802,4

Role of the hydro sector in the Cuban electricity system

All Cuban HPPs are owned by UNE by means of EMFRE (*Renewable Energy Company*). Water use for hydropower electricity generation is subordinated to irrigation and population supply. For

SHP that works as a run-of-river scheme, they operate very dependent on seasonal and in site climate conditions. Cuba only has 33 run-of-river SHP that operate 24 hours a day, every year. The rest of Cuban run-of-river SHP operates between 12 and 18 hours a day as year average. A strong seasonal electricity variability is shown in Figure 9 by means of "El Dian", a typical Cuban RoR SHP (Peña Pupo et al., 2020).

Figure 9. *Electricity generation in a typical RoR Cuban SHP*

For grid-connected HPP, only Hanabanilla HPP works as an Electric System secondary frequency compensator, regulating frequency or voltage, as Electric Systems demands. The rest of grid-connected SHP are subordinate to irrigation that is the most important use of Cuban reservoir. The SHP plant factor (low operation nominal power) depends on the agricultural plans. Generally, the Cuban SHP work at 24 hours with a very low plant factor, usually 50 per cent or less in most units. The typical behaviour of grid-connected Cuban HPP is shown in Figure 10. Hanabanilla 43 MW HPP (Figure 10) contributes between 40 and 80 per cent of monthly Cuban electricity generation (see Figure 10). Total electricity from grid-connected HPP is slower dependent on seasonal and in-site climate conditions due to reservoir flow regulation, but, droughts approximately every six years, affect electricity generation.

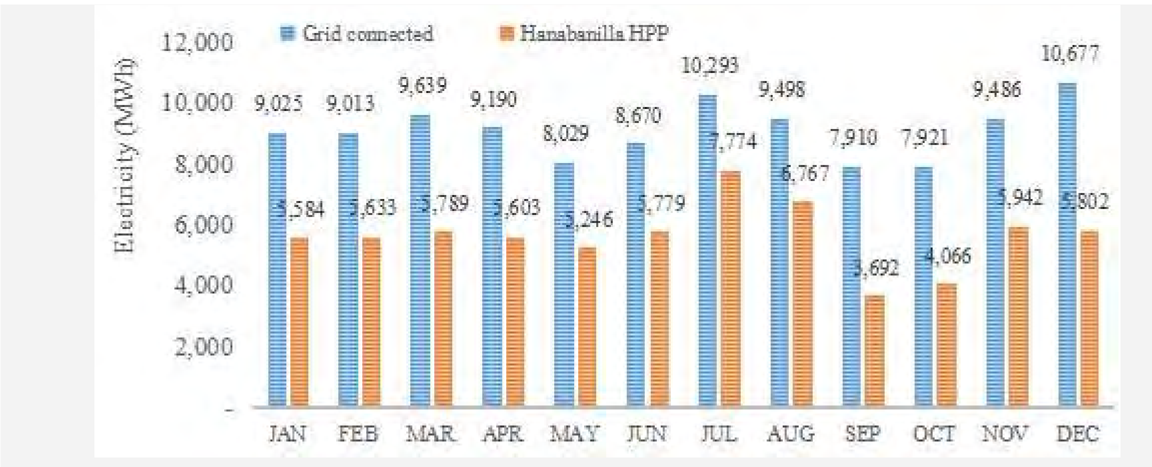


Figure 10. *Electricity generation of connected Cuban SHP.*

Droughts, especially those associated with “El Niño” episodes, have caused enormous impacts during the past 15 years and are projected to severely affect the Caribbean region in the future. For this reason, specific solutions must be implemented to reduce the risk of lack of electricity production by SHP plants as those foreseen in the National Plan to Confront Climate Change, known as “Tarea Vida” (Project Life). On the other hand, it is important to stress that half of the country’s hydropower potential lies in protected regions with a high biodiversity value, one of the reasons why hydropower has not been developed in Cuba on a larger scale until today (Morales Pedraza, 2018).

Development plans of Pumped Storage power plants

According to Vasudevan et al. (2021), only PHP (see Figure 4), compressed air energy storage (CAES) and thermal energy storage (TES) are technically and economically viable options for bulk energy storage requirements of the grid due to their high capacity and lower cost of energy storage. Among those options (Peña Pupo et al., 2018), PHP is technically mature and has a higher lifetime, higher capacity, lower cost of energy storage and a lower operation and maintenance cost.

The foreseen installation in Cuba of 700 MW in PV and 680 MW in wind variable energy (Ministerio de Comercio Exterior e Inversión Extrajera [MINCEX], 2019) requires to increase in Electric System storage capacity. In Cuba, they have been studied around 30 places with very good hydrological, geological and topographical conditions for the PHP construction, located in the three geopolitical regions of the country: west, centre and east. In the western part 11 places have been identified located in Rosario's hills with excellent location for their proximity to the high consumption and generation centres of the country. In the central region 4 places and the eastern region 15.

After two years of variants evaluation with 30 places in Cuba, were defined two places with high potential and ideal conditions for the hydraulic energy storage. One site in the central region, inside the Guamuaya (Figure 1) and another one in the eastern region known by “Sierra de Cristal” belonging to Holguín. This last place takes advantage of the opportunity to have one reservoir already built (see Figure 11) with excellent hydrological and topographical characteristics. That’s why a feasibility study of one PHP of 200 MW in the east of Cuba (Mayarí, Holguín) was completed in 2020 (del Campo, 2020).

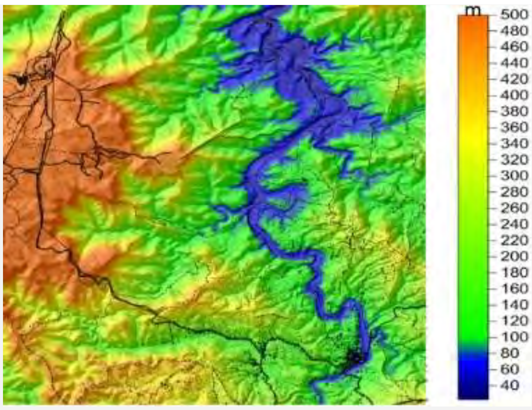


Figure 11. *Topographical conditions of Mayarí reservoir (Peña Pupo and Hidalgo, 2019).*

Seven variants of layouts were analyzed in function of the water conduction type and location of the higher and lower reservoirs (see Figure 12). Also, three positions for the location of the higher reservoir were analyzed. As a lower reservoir, it considered the already built reservoir in a Mayarí reservoir. The selected variant, was variant one (Figure 12), it has ideal conditions according to the geological study. The height differences oscillate between 350 and 450 meters in relatively short longitudes (2-3 km). The relationships between the penstock longitude and the hydraulic head (L/H) are smaller than 10, which is the value considered as a technical-economic feasibility index for PHP construction. In all the studied variants the L/H relationship oscillates between 5 and 7. Another factor of relevance constitutes the simulated reservoir hydrological guarantees of 100 years.

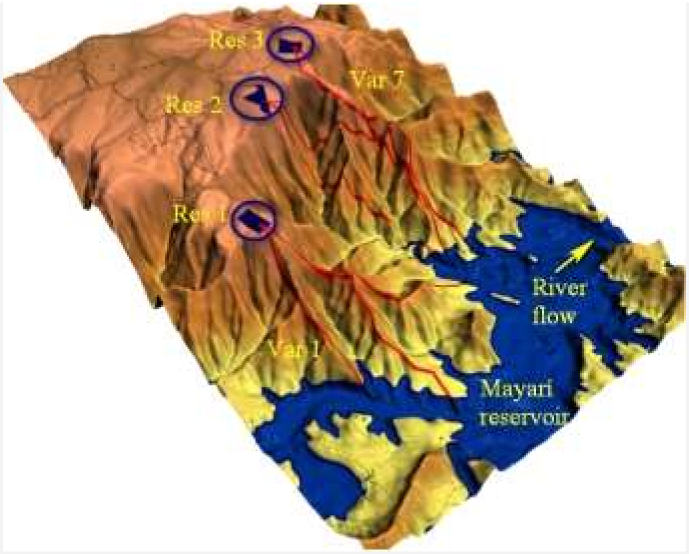


Figure 12. *Variants and reservoirs location evaluation.*

For the Cuban Electric System, the main advantages of PHP are increased grid flexibility, better integration of variable renewable energy like PV and wind, lower cost of electricity, and reduction of CO_2 emissions by use of a renewable energy source. The construction of PHP in Cuba a is a necessary challenge, and technical-economically feasible (Peña Pupo and Hidalgo, 2019). It constitutes a necessary investment in electrical infrastructure for the economic development of the country. Due to their nature of being capital intense, is suggested the evaluation of the possibilities of foreign investment participation (del Campo, 2020).

Current Challenges

Cuban Hydropower sector has to deal with some challenges to increase capacity and flexibility at lower operation costs. Considering new technologies like variable speed hydro in some built reservoirs can improve hydropower efficiency. To accelerate foreign investment to refurbish old low efficient SHP is another important topic. Considering automation and control systems refurbishments of an existent SHP and work in the integration of SHP in microgrids and smart grids is a necessary issue to increase HPP operation efficiency. Lastly, due to the limited scientific and technological capacity of the hydropower sector, it is recommended to guarantee Universities integration in the elaboration of future renewable energy plans.

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IV.6. Energy storage: technologies and possible applications in Cuban electric grid

Miguel Castro Fernández, Rafael Pomares Tabares & Miriam Vilaragut Llanes

Introduction

Cuba has opted for an energy system development supported by renewable energy sources (RES) in order to respond to the growth of electricity demand. The share of RES generation is expected to increase up to 24% of the total energy served to the National Electric Power System (NEPS) in the 2030.

Even though the increased amount of RES in the Cuban electric system has many positive impacts, it is also necessary to recognize challenges connected with the utilization of RES generation. Utilization of RES requires implementation of new generation and connection technologies, and injection of weather dependent variable generation in the power system sets new requirements and challenges for maintaining the balance between power generation and consumption. This forces system developers to think about how to maintain stability and safety of the electric power system by using complementary technologies such as energy storages.

It is anticipated that the 2020s will be the decade, when the energy storage market will make the breakthrough. With the increasing demand for electricity storage from stationary and mobile applications, the total stock of electricity storage capacity in energy terms is expected to grow to 11.89-15.72 TWh if the projection that by 2030 the RES installation is duplicated.

A storage technology recently being imposed with greater force is battery electric storage systems (BESS). The technology had one of its first applications with the installation of 12 MW in the Atacama desert in November 2009, in Chile. The BESS was supplied by two companies AES Energy Storage and A123 Systems. It was used to regulate the frequency and reduce the required capacity of spinning reserve in the system that supplied electric loads of the mines in the region (EVWIND, 2009). The European Union reports around 3 GWh of BESS capacity installed and in operation in its territory, and the capacity is expected to grow up to 12.8 GWh by 2025 (SolarPower Europe, 2021).

Frequency stability and required capacity of spinning reserves are the two main problems to be solved in the Cuban NEPS, when the share of variable renewable generation is increased in the system. Energy storages serve feasible solutions for these problems. Already in the mid-80s, a possibility of incorporating pumped hydro storages to support the operation of the NEPS was evaluated. More recent projects have been carried out in Isla de la Juventud, where a BESS is proposed to increase the penetration of solar photo voltage (PV) power generation plants in this region. Isla de la Juventud is an isolated system with no connection to the grid of the main island.

Technologies and operation

Energy storage is a process that allows energy to be transformed and stored to another body or system to later convert it into useful energy. The most typical forms of stored energy are chemical energy (batteries), heat, electric field (capacitors), rotating mechanical energy (flywheels), and potential energy (water reservoirs of hydro power). There are three basic lines of application of energy storage: energy management (economic dispatch, emission reduction), energy quality (uninterrupted service, frequency regulation) and transportation (electric vehicles).

One of the fundamental challenges in the operation of electric power systems (EPS) is the balance between the supply and the demand. Generation must be equal with consumption in every second. Operators of deregulated EPSs operating in SPOT markets with high levels of RES penetration can have considerable economic losses associated with variable renewable energy (VRE) production due to production forecast errors. If momentary VRE production shorts from the predicted value, the responsible operator has to pay the costs caused by the compensation of the misbalance between expected and realized production. The compensation is carried out by activating generation reserves. For example, the transmission system operator 50 Hz Transmission in the northeast of Germany spent more than 1 billion Euros in 2015 on rescheduling measures resulting from the forecast errors (Electric Energy Storage Systems, 2017).

Problems with storing of energy at high capacity have led to the need to have high levels of spinning reserve (units running without doing work), which increases the operation costs. Energy storage technologies (EST) have been used since the beginning of EPSs; the first electric city light at U.S.A was supplied by electricity from a DC generator combined with battery storage, and the first large power station used the energy of falling water and converted it into AC electricity (Woodworth C.A., 2016). Many local energy storages (batteries) were also used later in Germany around 1930 to stabilize and support the power system, especially during the night. Energy storage comprised about 2 % of the installed power (7 GW) at that time (Electric Energy Storage Systems Book, 2017).

There are several factors that affect the need to use electric energy storages:

- The temporal variability of weather dependent renewable energy production.
- The need to respond to short-term disturbances in the electrical network, avoiding the start-up of reserve generating units.
- Co-power supply irregularities.
- Facilitate the planning of electricity generation systems.
- Reduce momentary required generation power during peak hours by discharging energy storages.

Different energy storage technologies, their typical power capacities and operation periods related to their energy capacities are presented in Figure 1.

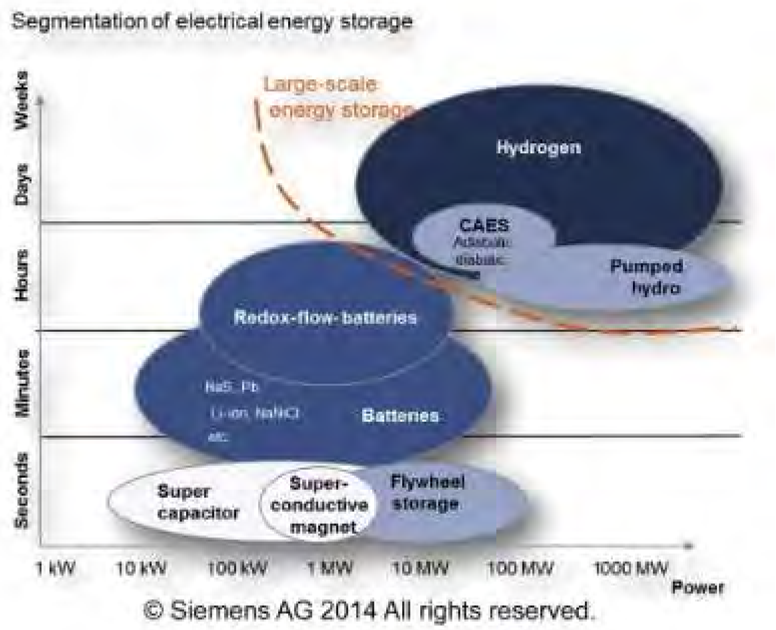

Figure 1. *Overview of storage technologies and their typical power and capacity ranges. Source: (Erik Wolf, 2015)*

Table 1 shows the state of maturity and some specific characteristics of the selected EST. In the table CAES refers to compressed air energy storages and SMES to superconducting magnetic energy storages.

Table 1. Comparison of the development status and other characteristics of different energy storage technologies. Source: Valdovinos, F. y Otárola, R. (2008)

Characteristic	Pumped Hydropower	CAES	Flywheels	Batteries	SMES	Supercapacitors	Thermal
Energy Range MJ	$1,8x10^6$-$36x10^6$	18 $x10^4$-$18x10^6$	1-18.000	1.800-180.000	1.800-$5,4x10^6$	1-10	1-100
Power Range MWe	100-1.000	50-1.000	1-10	Lead acid – 60-180 Nickel Metal hydride – 370 Li-ion – 400-600	10 – 1.000	0,1-10	0,1-10
Overall Cycle Efficiency	64-80%	60-70%	~90%	~75%	~95%	~90%	~80-90%
Charge/Discharge Time	Hours	Hours	Minutes	Hours	Minutes to Hours	Seconds	Hours
Cycle Life	≥10.000	≥10.000	≤10.000	≤2.000	≥10.000	>100.000	>10.000
Footprint/Unit Size	Large if above ground	Moderate if under ground	Small	Small	Large	Small	Moderate
Siting Ease	Difficult	Difficult to moderate	N/A	N/A	Unknown	N/A	Easy
Maturity	Mature	Early development	Early development	Lead acid mature, others under development	Early R&D stage, under development	Available	Mature

Note: 1 MJ=277 Wh

Another possibility to classify EST is a comparison between their technical properties. For this purpose a group of indicators has been proposed, such as: output power or power capacity, storage capacity, depth of charge, charging ratio, discharge power ratio, AC voltage requirements, duty cycle requirements, portability requirements, state of charge, depth of discharge, self-discharge, energy density, start-up time, ramp-up time and specific costs (Electric Energy Storage Systems, 2017).

Possible applications in Cuban electric grid

Possible problems in Cuban electric power systems rising from the increased share of VRE generation in the system are associated with a high variability of momentary residual load and reliability of the forecasting of VRE generation. Residual load is the difference between the momentary load and VRE generation. Residual load must be supplied by other generation sources or by dispatching of the load. The bigger the variability of the residual load, the more flexibility and capacity of the controllable generation is required to balance the system.

Some authors consider that the mean value of the forecasting error of renewable generation is about 2.5% over for 24 h (Electric Energy Storage Systems, 2017). However, the real error could be much higher in a Cuban type system located on an island, where changes in solar radiation intensity levels, to name one main energy source, can occur in seconds. Figure 2 shows the variability of the energy production of a photovoltaic plant on the Isla de la Juventud with the presence of cloud cover, both variables obtained over a year. The horizontal axis shows the months of the year, while the vertical axis shows how the energy production and cloudiness vary during that same year. As can be seen, the energy production in the park is directly related to the presence of clouds in the territory where the photovoltaic park is located, according to what was established by the author of the work (Soto Calvo, 2017).

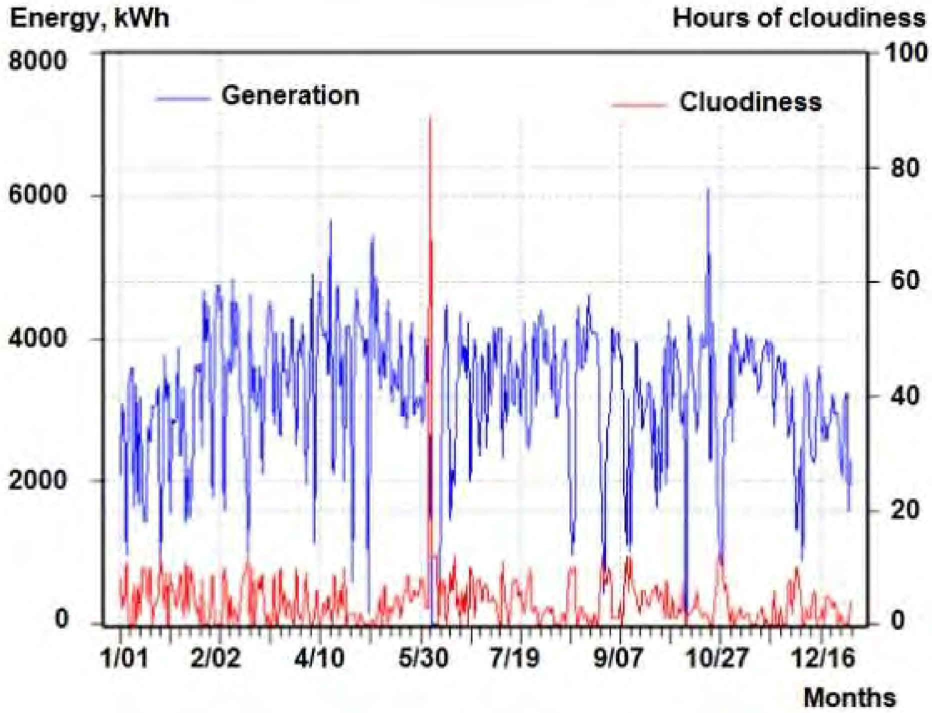

Figure 2. *Variability of the electricity generation of a photovoltaic plant with the variation of intensity of solar radiation (represented by the variation of cloudiness). Source: (Soto Calvo, 2017)*

The introduction of the EST in the Cuban NEPS should consider the needs of its operation and safety, because it is an isolated system. Taking this criterion as a premise, the main tasks to be responded by a EST are the frequency control of the NEPS and the reduction of the needed spinning reserve capacity. These tasks require fast responding storage capacity such as BESS and pumped hydropower technologies.

Impact of a pumped hydro storage plant (PHSP) in the Cuban NES

The expected effects of a pumped hydro storage plant on the operation of the Cuban NES are:

- It is a plant that is mostly useful at the peak load, which consumes cheaper energy in low-demand hours to store an amount of energy and replaces more expensive power generation in peak-demand hours.
- It is a plant with a very fast response capacity (in few tens of seconds it can rise from zero to its maximum power when already connected to the network), which makes it ideal to cover situations of emergency exits of generating units, reducing the magnitude and time of impact on consumers, as well as losses to the national economy. It is a very fast primary regulation operating reserve.
- It would allow the NES to operate with a lower spinning reserve, which reduces operating costs.
- Ensures a higher generation of the base load units during the hours of less demand, increasing their operation efficiency and reducing their operating cost indexes, in fact flattening the daily load curve of the NES during early mornings, giving a solution to one of the most serious problems that the efficient operation of the Cuban NES has.
- Facilitates the penetration of RES in the NES.
- It can participate in the regulation of the frequency of the NES, although this would be detrimental to its use at the peak.
- It can cooperate in regulating the voltage and reactive power of the NES, working as a voltage regulator at extreme moments.

(González Barboza, 2014) has analyzed the profitability of the possible investment in a pumped hydro storage plant in the Cuban NES. The premises of the pumped hydro storage were: operating power of 120 MW with an efficiency of 75%, 6 hours of daily operation in generating mode (25%) and 8 hours in pumping mode for 330 days a year (162 days under the conditions of the winter load curve and 168 under the conditions of the summer load curve). The analysis showed that the operation of the pumped hydro storage was not economically profitable. The calculated net present values (NPV) for a period of 25 years of operation was negative.

A possible variant of improving these results would be to associate, to the PHSP investment, a photovoltaic park connected to the grid (PVPCG) that would reduce the energy consumption of the grid by the plant in its pumping operation regime during business hours. afternoon, which corresponds to the departure of the midday peak and preparation for the coverage of the night peak; This consumption reaches values of 30 MWh on average, which would be worth analyzing from the point of view of what the investment of the PVPCG would represent and its impact on the network in a comprehensive manner.

Impact of the use of BESS technology on the Cuban NES

In response to a request from the Electricity Union of Cuba, an analysis of the possibility of increasing photovoltaic penetration by 2030 with the use of BESS was carried out. As a result of this study, it was concluded that under the conditions and scenarios analyzed, the Cuban NES can adopt up to 1200 MW of solar PV generation capacity supplemented with 470 MWh BES capacity. The feasibility of the system was analyzed for minimum, medium and maximum power demands with two charging/discharging daily cycles of the BESS (CIPEL, 2016).

The evaluating was done under conditions of stable and dynamic states of the same for the conditions of coverage of the electrical demand in regime of minimum, medium and maximum demand, considering the loading two (2) times and unloading three (3) times a day of the BESS, shown in Figure 3 (CIPEL, 2016).

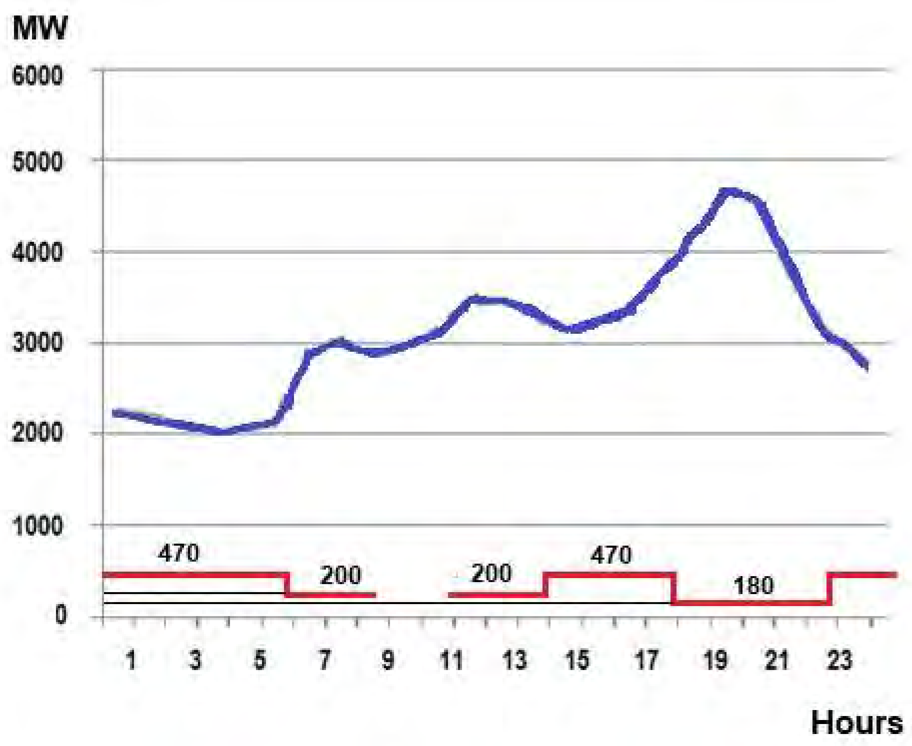

Figure 3. *Behavior and use of BESS to increase PV penetration levels in the Cuban NES. Source: CIPEL (2016).*

The solid blue line represents the typical daily load curve in the Cuban NES. The red sections represent the times of charging and discharging the batteries (470 MW charge at dawn and 200 MW discharge at the morning peak; 200 MW discharge in the afternoon peak; 470 MW load in the afternoon and 180 MW discharge in the evening peak).

By operating in this way, the BESS ensures an increase of up to 1,300 MW of photovoltaic source to be installed in the system, about 500 MW more than planned for 2030 in its first variant, with reliable exploitation of the Cuban NES, both in static conditions as dynamic.

Conclusions

What has been seen so far is based on the use of BESS technology and the pumping of water for storage, but it must be taken into account that trends may change according to some authors. For example, (Kaps, Marinesi, Netessine, 2021) argue that despite current investment being focused on batteries, and other authors such as (Kittner et al. 2017; Diouf and Pode 2015; Tsiropoulos 2018) suggest that batteries may be the future technology of choice to store electricity for several hours or days, they consider that cheap and low-efficiency technologies, such as thermal, will be adopted before expensive high-efficiency ones. like lithium ion batteries.

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IV.7. PhD Research work

IV.7.1 Reverse modelling of plasma gasification with gasification temperature and produced gas H_2/CO ratio requirements

Jorge Jadid Tamayo Pacheco, Angel Luis Brito Sauvanell and Jukka Konttinen

Abstract

The thermal conversion of organic materials to hydrogen-rich gas, which can then be used for the synthesis of additives or second-generation biofuels, is a possible route to reduce fossil fuel consumption and at the same time reduce the negative environmental impact of waste. One of the techniques studied to carry out this transformation is gasification by plasma with air and steam as gasifying agents, a complex process in which various operational parameters are interrelated. When strict gas quality requirements are established in this process, correlations are generated between the operational parameters that make it difficult to predict its behaviour. That is why inverse computational modelling of the process will be developed using a thermochemical equilibrium model with a focus on the dependency relationships between its variables and its relationship with the process performance.

Introduction

In recent years, the energetic valorisation of carbonaceous materials has been a matter of global concern for developed countries and for those that are still developing; because, in addition to the direct economic benefits that could be generated, it also generates environmental benefits and contributes to satisfying the growing energy demands. This matter is included in the sustainable development objectives also known as the 2030 Agenda, from which it calls for increasing the proportion of renewable energy and reducing the negative environmental impact of waste.

The use of these bioenergy sources is closely linked to the development of efficient techniques that allow this production to be competitive with the use of conventional fuels. This study will focus on one of the thermal-conversion techniques: gasification. Gasification makes it possible to convert a solid material with a low calorific value and difficult to handle into one that is easier to use from an energy point of view: fuel gas (Basu, 2018).

The energy applications of the gas produced are diverse, such as the generation of heat and electrical energy, and the production of biofuels or additives to traditional fossil fuels. For each application, there are requirements that the gas must meet, such as tar content, calorific value, the molar ratio between H_2 and CO, etc. The low tar content is a common restriction and is associated with the temperature to which the producer gas is subjected, that is, high gasification temperatures (greater than 1200 degrees) represent low tar contents (Basu 2018).

For the purposes of this study, it will be considered as an application, the obtaining of a gas-rich in hydrogen and devoid of tars with conditions to be used for the synthesis of biofuels or fuel additives that require an H_2/CO ratio equal to 2, such as the case of methanol synthesis and biofuel synthesis using the technique known as Fischer-Tropsch (Im-orb, Simasatitkul, and Arpornwichanop, 2016). The gasification process can be classified according to the origin of the energy required by it in autothermal or direct gasification when this comes from the combustion (internally in the reactor) of a part of the fed material or the allothermic or indirect gasification when the energy required by the process it is supplied externally (Dahlquist, 2013). This gives indirect gasification greater controllability of the process, generating a better-quality fuel gas (Agon and Helsen, 2018).

Regarding indirect gasification, the use of thermal plasma is a novel concept (Heidenreich and Foscolo, 2015). As can be seen in figure 1, in this thermal conversion technique, in addition to the material to be gasified, the gasifying agent(s) is introduced and the thermal plasma is used as a heat source for the gasification process, obtaining a fuel gas composed mainly of H_2, CO_2, CO, H_2O, N_2. and vitrified slag. Although the plasma gasification (PG) concept was originally designed for the treatment of hazardous waste, it was later extended to generate high-quality synthesis gas from multiple materials (Hrabovsky et al., 2017).

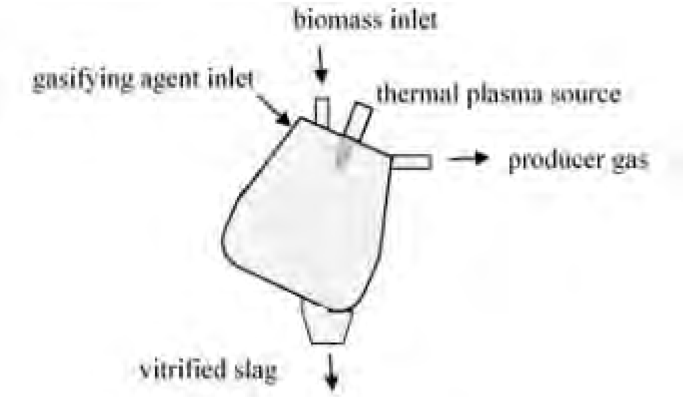

Figure 1. *Plasma gasification process reactor.*

Compared to other thermo-conversion techniques, PG has few plants worldwide. Alter NRG is a company with extensive experience since it acquired the American Westinghouse Plasma in 2007 and has built several plants in Japan, China, the United Kingdom and India. Other companies that have developed technologies for PG are Europlasma, Plasco energy group, InEnTec, Solena Group, PEAT International, and SRL Plasma (Achinas, 2019). These companies have created pilot plants of various sizes including large commercial projects.

In the consulted literature, there are reported recent attempts to develop plasma-assisted gasification technology to convert the waste in small facilities, that is, with capacities less than 10 tons per day (tpd) (Li, Li, and Wei, 2020; Sturm et al., 2016; van der Walt, Jansen, and Crouse, 2017). For example, the HelioStorm technology from Cogent allows converting 4 tons of municipal waste into 4 MW of excess electrical energy and the catalytic hydrogasification technology belonging to Blueplasma Power can convert organic waste into a gas and then this into fuel additives.

Despite its benefits, PG has not been very successful, mainly due to the high capital cost of a commercial plant and its technological immaturity. Furthermore, the moderate level of community preparedness is discouraging for governments and companies to invest in such technology, to which are added its extreme operating conditions and possible security problems (Munir et al., 2019). In Cuba, the plasma gasification technique has not been applied, but given the potential of organic waste, it could be of interest once it is economically feasible.

Several studies on PG have been aimed at the thermodynamic analysis of the process, including the prediction of the composition of the gas produced as well as energy and energetic calculations (Kokalj, Arbiter, and Samec, 2017; Mountouris, Voutsas, and Tassios, 2006) while others have been more focused on evaluating the performance of the model with changes in the independent variables, or changes in the characteristics of the material to be gasified or the type of gasifying agent (Indrawan et al., 2019; Janajreh, Raza, and Valmundsson, 2013; Mazzoni, Ahmed, and Janajreh, 2017; Mazzoni and Janajreh, 2017).

Specifically, gasification by plasma for the purpose of producing a gas-rich in dihydrogen has had recent research (Favas, Monteiro, and Rouboa, 2017; Tavares, Ramos, and Rouboa, 2019). In these works, the use of water steam as a gasifying agent or as a plasma gas is proposed because of its beneficial effect on the formation of dihydrogen, while completion of oxygen for the partial oxidation of carbon is achieved with the addition of air, air enriched with oxygen or pure oxygen. The use of equilibrium models is also a common element of these works since this type of model is considered realistic for this type of process (Hrabovsky et al., 2017).

Notwithstanding the valuable results of the aforementioned research, some knowledge needed must be pointed out:

a) For the sizing and the operation of a plasma gasifier with air and steam, a procedure is required to determine the operating conditions that optimize the process performance criteria meeting the quality restrictions of the producer gas. To achieve this, in the present work will be used the inverse approach modelling is based on a graphical method.

b) The correlation between the operational parameters that are created when the process is subjected to restrictions such as producer gas temperature and H_2/CO relation has not been taken into account, nor has the simultaneous effect of the correlated parameters, aspects briefly mentioned in (Zhang, 2011), but it has not been determined in a mathematical and analytical way. This correlation between two operational parameters Plasma Energy Ratio (PER) and Steam Biomass Ratio (SBR) is evidenced in Figure 2, where the restrictions of the molar ratio $H_2/CO = 2$ and gasification temperature to 1200 °C limit the operating region to a curve.

c) The effect of a group of process input variables on other output variables and performance indicators has been studied, but there is no description of which effects are stronger and more decisive for high hydrogen content gas production, or which could be neglected. In the present work, this will be done through local and global sensitivity analysis methods.

d) The equilibrium models overpredict the carbon conversion in comparison with experiments about PG. Thus, is needed best understanding of the relations between operational parameters in PG to achieve full carbon conversion. To solve this, a mathematical model of full carbon conversion will be developed based on the results of experiments about the kinetic of high-temperature gasification with thermobalance in CO_2 and H_2O atmospheres.

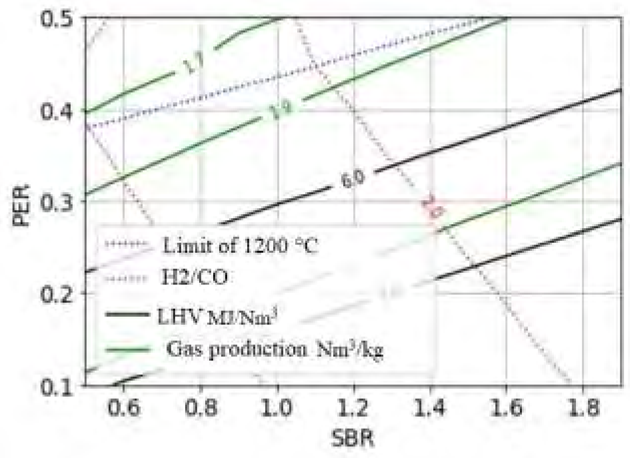

Figure 2. *Level curves. Modelling of PG of sugarcane bagasse (source: own elaboration)*

Firewood as energy source for cooking

Research problem

From the exposed criteria a) to d) it is inferred as a **scientific problem** to solve:

Insufficient knowledge about the simultaneous effects of operational parameters on the performance of plasma gasification with air and steam, as well as its relationships with other process variables when it has strict requirements for temperature and H_2/CO ratio of the gas produced.

In correspondence with the declared scientific problem, the **general objective** is defined as:

To develop mathematical modelling with an inverse approach and sensitivity analysis of the plasma gasification process with air and steam as gasifying agents.

Novelty

The **theoretical contribution** that gives scientific novelty to this research consists of:
The characterization and mathematical formulation of the plasma gasification process with air and steam when there is a correlation between its operational parameters due to producer gas quality restrictions.

Importance: social, economic, environmental

Although this research is essentially manifested in the field of technical sciences, its social importance is noteworthy, since it has a possible impact on the future development of technologies for the generation of electricity and second-generation biofuels, which constitute a growing demand. Another indirect positive aspect is the generation of employment mainly in the activities of collection, transport and processing of waste. And no less important is the use of vitrified slag as a construction material.
From the environmental point of view, its possible favourable impact has to do with better waste management and this has an impact on the hygiene of the populations, in addition to avoiding the emission of bio-methane into the atmosphere. To take advantage of these positive aspects, it is necessary to correctly design and operate gasification plants and thus avoid the emission of pollutants into the atmosphere.
From the economic perspective, PG of wastes could generate economic benefits in certain favourable scenarios characterized by high oil prices and a decrease in investment capital as part of the process of learning and maturing technologies.

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IV.7.2. Mathematical model of the culture of the microalgae Chlorella vulgaris in an outdoor falling film photobioreactor

Orlando Gines Alfaro Vives, Siannah María Más Diego and Rafael Matos Durán

Abstract

Models describing the interaction between algae and bacteria in photobioreactors have not been fully studied. In studies that have handled the subject in the past, a calibrated model for outdoor falling film photobioreactors has not been found. The existing kinetic models do not describe all the processes associated with the growth of the *Chlorella vulgaris* microalgae with and without pH control, nor do they allow to accurately simulate the growth process in the transition zone between the exponential phase and the stationary phase of growth. The temperature has not been incorporated as a state variable in the models for photobioreactors. The latter allows us to correlate important variables such as ambient temperature, wind speed, relative humidity with the temperature of the culture suspension and would facilitate the location of the photobioreactor. A new kinetic equation for the growth of microalgae is proposed and validated. This equation is incorporated into an integrated microalgae bacteria model, which is validated with experimental data from a 3500 m^2 outdoor falling film photobioreactor. The photobioreactor uses porcine liquid residual liquid as the sole source of organic matter and nutrients. The new integrated model incorporates the calculation of the mass transfer coefficients of the gases involved in the process.

Introduction

Productive and social activities and processes require large amounts of water. A direct consequence of the use of water is the production of liquid waste that requires treatment. This allows the water to return to the environment and that the hydrographic basins and oceans assimilate it without causing environmental damage, as projected in the National Environmental Strategy 2016/2020.

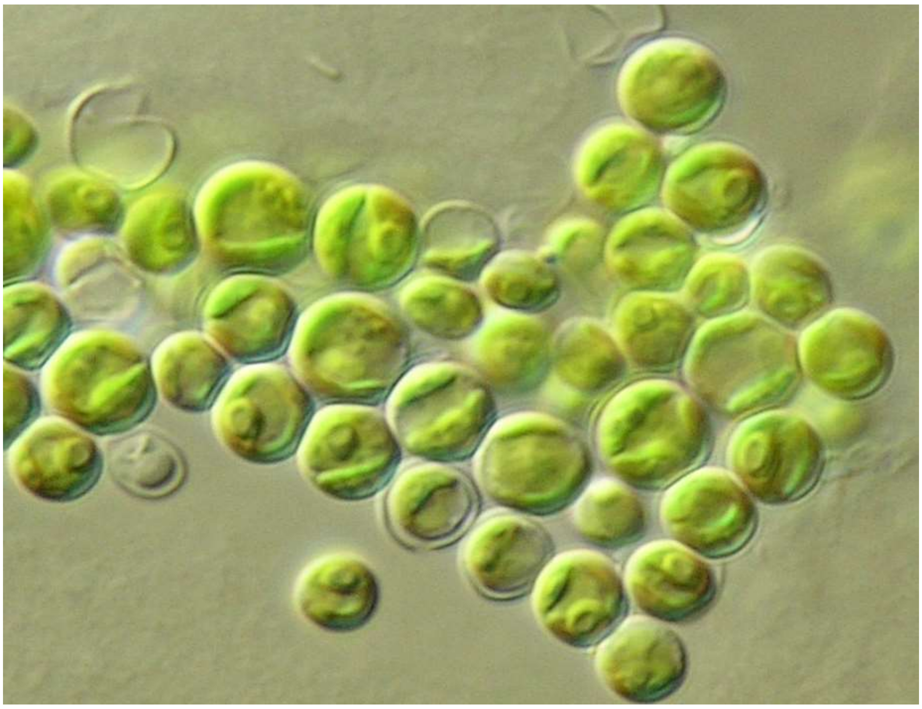
One of the most pressing problems in Cuba and in general throughout the world is the reduction of the polluting load of liquid livestock and industrial waste with a high organic load. Due to their aggressive nature, liquid pig, poultry and alcohol distilleries waste contaminates the water and the soil, making them very expensive to dispose of.

Microalgae-bacteria interactions have long been used for wastewater treatment in waste stabilization ponds (WSP). This type of treatment has been intensively implemented worldwide since World War II. As an example, in 1990 there were more than 7,000 WSPs in the United States representing more than 1/3 of the operating wastewater treatment plants (García, Mujeriego, and Hernández-Mariné, 2000). Due to their low cost, these systems are the most widely used in Cuba. The important role of microalgae (as well as bacteria) in the processes of elimination of pollutants that occur in WSP was evidenced in the studies by Myers (1948). However, interest in WSPs waned after 1990, especially in developed countries due to several reasons, but in particular, the high content of microalgae in their effluents that makes it difficult to comply with the usual effluent standards for total suspended solids (Park, Craggs, and Shilton, 2011).

To solve this problem of conventional WSP, high-speed algae ponds (HRAP) first appear, which were developed in California in the late 1950s (Oswald, W. J., Gotaas, H. B., Golueke, C. G., Kellen, W. R., Gloyna, E. F., and Hermann, 1957). HRAPs are shallow channel ponds with mechanical agitation of mixed liquor to increase microalgae biomass production and improve contaminant removal. In the 1980s, falling film photobioreactors were used at the Solar Energy Research Center in Santiago de Cuba for improving HRAP. The culture suspension circulates with a depth never exceeding 1cm through these ribbed ponds. These systems allow high concentrations of microorganisms to be reached, thus reducing the cost of separating the biomass.

In recent years, the search for fuels such as biohydrogen, bioethanol and alternative biodiesel neutral to combat climate change, has revived great enthusiasm towards microalgae and bacteria systems such as falling film photobioreactors (Alfaro-Vives et al., 2017; Arenas et al., 2017). However, the production of biofuels from microalgae has a prohibitive price. The interest is currently much more focused on developing wastewater treatment systems with a neutral energy footprint that, at the same time, can produce marketable products and wastewater that can be reused (Alfaro-Vives et al., 2017; Arenas et al., 2017). Compared to conventional wastewater treatment systems, the potential for cost savings including electric power is large enough to promote falling film photobioreactors independent of biofuel production (Suganya et al., 2016).

The culture of the microalgae *Chlorella vulgaris* and a heterotrophic microbial consortium in a falling film photobioreactor is a system capable of reducing the pollutant load in terms of Chemical Oxygen Demand (COD) by up to 80%, in addition to reducing the content of nitrogen and phosphorous in the wastewater to acceptable values for dumping according to Cuban standards. At the same time, it produces biomass rich in proteins, vitamins and other biofactors that can be used in the production of vegetable fortifier or biodiesel. Because of this, the system is of great interest for the development and implementation of the Agricultural Strategy for Integrated Management of the Ministry of Cuba's agriculture.



Microalgae Chlorella (source: phytocode.net)

Previous experiences allow us to affirm that productivity of 34 to 40 $g \cdot m^{-2} \cdot d^{-1}$ can be achieved in these facilities. Results that were not possible in the existing experimental facilities at CIES, nor in the 3500 m^2 treatment plant that operated in the feedlot pig from “El Brujo” in Santiago de Cuba, where average productivity of 28 $g \cdot m^{-2} \cdot d^{-1}$ was reached and the desired results were never achieved in terms of removal of organic matter.

Compared to conventional technologies, the inner workings of microalgae wastewater treatment systems in photobioreactors have been less studied, and in particular the interactions between microalgae and bacteria. In these systems, microalgae can promote or inhibit the growth of bacteria and vice versa (Awuah, 2006; Marsollier et al., 2004; Pierong, 2014; Ruiz-Marin, Mendoza-Espinosa, and Stephenson, 2010). The physical, chemical and biological processes that take place in these systems (for example, growth, decomposition, light attenuation, mass transfer of gas to the atmosphere) occur simultaneously and are interdependent (Decostere et al., 2013; Solimeno et al., 2015). Furthermore, the rates of these processes depend on constantly changing environmental variables, such as light intensity and temperature. Within this framework, it is necessary to obtain information on this complexity that will help to create a body of knowledge on the interactions between microalgae and bacteria. A deep and realistic understanding of the inner workings of these systems is necessary to predict performance and optimize reactor design. Mathematical models represent a powerful tool for obtaining information on complex systems such as photobioreactors for the cultivation of microalgae.

Simplified schematic representation of the model

To facilitate understanding of the model, the figure shows a general simplified schematic representation of the conceptual model that describes the complexity of microalgal-bacterial interactions.

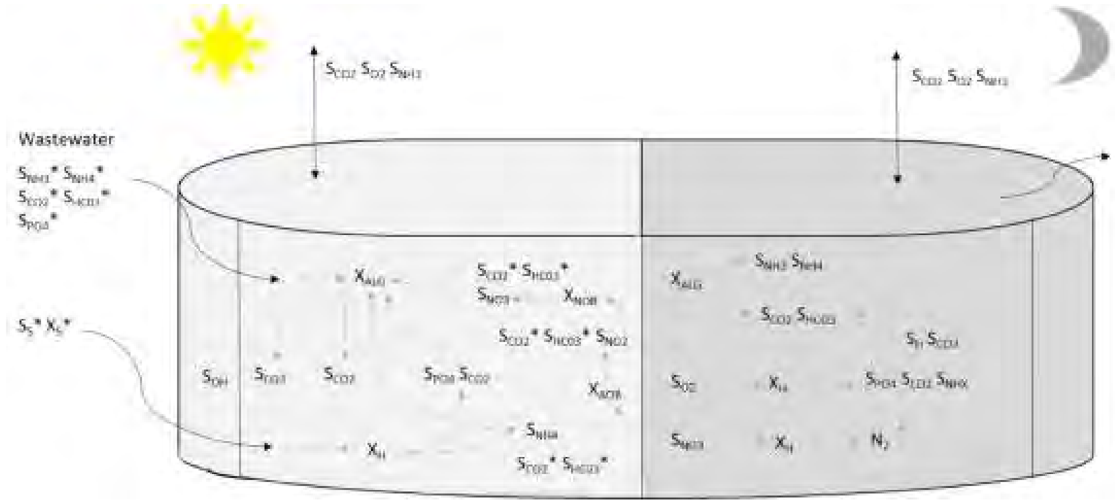


Figure 1. *Simplified general schematic representation of the integrated conceptual model showing the main interactions between algae and bacteria in a high-speed algal pond, during the day (left) and at night (right). The components that enter the ponds with the influent are marked with * and the processes are indicated with arrows*

Photosynthetic processes are activated by light. While the microalgae (X_{ALG}) grow, they fix the inorganic carbon (S_{CO2} and S_{HCO3}), consume substrates (S_{NH4}, S_{NO3} and S_{PO4}) present in the wastewater and supply the oxygen (S_{O2}) required by the heterotrophic bacteria (XH) to oxidize the organic material. During the oxidation of bacterial organic matter, CO_2 is produced and is available for photosynthesis and nitrification. Nitrification is a two-step process: the first ammonium oxidizing bacterium (X_{AOB}) converts ammonia and ammonia to nitrite (S_{NO2}) and the second nitrite-oxidizing bacterium (X_{NOB}) converts nitrite to nitrate (S_{NO3}) (Costache et al., 2013; Henze et al., 1999; Moreno-Grau et al., 1996). As a result of the activity of microalgae, the concentrations of hydroxide ions (S_{OH}) and the pH increase. With increasing pH, the bicarbonate-carbonate equilibrium shifts, pushing carbon species towards the formation of carbonate (S_{CO3}), volatilization of lead and ammonia and phosphorus precipitation (Reichert et al. 2001; Sah et al. 2011; Solimeno, Acíen, and García 2017).

In the dark, both heterotrophic bacteria (X_H) and microalgae (X_{ALG}) have a net release of CO_2 through the oxidation of organic matter and endogenous respiration, respectively. With this release, the hydrogen ion concentrations increase and the pH decreases, the bicarbonate-carbonate balance changes and the carbonate is converted to bicarbonate (S_{HCO3}). This bicarbonate can be used again as a substrate in the presence of light. Microalgae respiration and bacterial growth reduce the oxygen level within the water. When oxygen levels are low, nitrate can become the primary source of oxygen and denitrification occurs. This process is carried out under anoxic conditions denitrifying bacteria that reduce nitrate (S_{NO3}) into nitrogen gas. In fact, denitrifying bacteria are considered the same heterotrophic (X_H) bacteria that, under oxygen depletion circumstances, can optionally use S_{NO3} instead of S_{O2}.

Microalgae and bacteria processes are influenced by temperature, which also affects chemical balance, pH, and gas solubility (Reichert et al., 2001; Sah et al., 2011; Solimeno et al., 2017; Solimeno, Gómez-Serrano, and Acién, 2019). Furthermore, in an outdoor falling film photobioreactor, excess dissolved oxygen and CO_2 are gradually transferred from the culture medium to the atmosphere.

As it can be seen, the models capable of integrating the interrelationships between algae and bacteria have been well studied, but certain points that are vitally important in order to better understand these processes have been neglected. Among them we can highlight:

- None of the models studied includes a limiting factor for the growth of microalgae and bacteria at high or low pH, despite the fact that high and low pH has been shown to reduce the growth rate of algae and bacteria.

- The models do not include the calculation of the gas mass transfer coefficients to the atmosphere and consider this parameter constant, despite the strong influence of these rates to achieve good predictions of the concentration of gases in the culture suspension.

- The phenomenon of heat transfer in photobioreactors is not taken into account in any of the models. This facilitates the calculation of the mass transfer coefficients on the principle of similarity between the phenomena of mass transfer and heat and allows the influence of important environmental factors such as ambient temperature, wind speed, relative humidity and location of the photobioreactor to be identified.

- All models oversize the effects of light availability by not taking into account a limiting factor for microalgae growth at high or low pH.

For all the above, the following Scientific Problem arises: The current explanations related to the physical, chemical and biokinetic phenomena associated with the cultivation of the microalgae *Chlorella vulgaris* in open-film, falling film photobioreactors, do not meet the expectations and need an increase in productivity per unit area and removal of organic matter.

The Research Object is the culture, in the liquid fraction of the pig residual with a high organic load of the microalgae *Chlorella vulgaris* and a heterotrophic microbial consortium in an outdoor falling film photobioreactor.

The field of action is the mathematical modelling of an outdoor falling film photobioreactor used in the culture process, in the liquid fraction of the porcine residual with high organic load, of the microalgae *Chlorella vulgaris* and a consortium of heterotrophic microorganisms.

As a way to solve the problem, the following research hypothesis is formulated: Is it is possible to develop, calibrate and validate an integrated mechanical microalgae-bacteria mathematical model capable of describing the treatment of the liquid fraction of the porcine residual with high organic load in an outdoor falling film photobioreactor? Then the complex physical, chemical and biokinetic

phenomena that take place can be understood, which will facilitate maximizing productivity per unit area and removal of organic matter.
The General Objective of this research is defined as: To develop an integrated mathematical model for the simulation of a treatment system for the liquid fraction of pig waste with a high organic load based on the culture of the microalgae *Chlorella vulgaris* and a consortium of heterotrophic microorganisms in an outdoor falling film photobioreactor.
To fulfil the general objective, the following are proposed as specific objectives:

1. Develop and calibrate a mechanistic mathematical model for microalgae (free of bacteria) and evaluate the sensitivity of the model's outputs with respect to a set of key input parameters, obtained in an outdoor falling film photobioreactor.

2. Develop, calibrate and validate a microalgae-bacteria integrated mechanistic mathematical model and evaluate the sensitivity of the model outputs with respect to a set of key input parameters obtained in a falling film photobioreactor used for the treatment of the liquid fraction of the pig residual with a high organic load.

3. Validate the model results by comparing the results with the experimental data obtained in a 3500 m^2 pilot plant.

The scientific contributions of this research are:

- A new kinetic mechanistic model of microalgae, which includes the effects of pH, is integrated into the mechanistic model of microalgae-bacteria.

- The heat transfer process from and to the culture suspension is integrated into the microalgae-bacteria mechanistic model, which facilitates the calculation of the mass transfer coefficients to the atmosphere, by the similarity principle, as in previous models they are considered constant.

- The integration to the model of the heat transfer process allows identifying the influence of important environmental factors such as: ambient temperature, wind speed, relative humidity and location of the photobioreactor on the temperature of the culture suspension.

- A new program is developed in MatLab / Simulink that simulates the growth process of the *Chlorella vulgaris* and a heterotrophic microbial consortium in a falling film photobioreactor, where the liquid fraction of the pig residue with a high organic load is used as the only source of organic matter and nutrients.

Therefore, at the end of this investigation, the multiple phenomena, (of mass and energy transfer, speed of chemical reactions, chemical equilibrium in aqueous solutions and light absorption), that intervene in the culture of the microalgae *Chlorella vulgaris* and a heterotrophic microbial consortium in an outdoor falling film photobioreactor.
The results derived from this research may be used to:

- Increase the efficiency and effectiveness of the culture process, in wastewater, of *Chlorella vulgaris* and a heterotrophic microbial consortium in an outdoor falling film photobioreactor.
- Predict the behaviour of the cultivation process, in wastewater with a high organic load, of the microalgae *Chlorella vulgaris* and a heterotrophic microbial consortium in an outdoor falling film photobioreactor as a function of the flow and volume of the liquid fraction of the pig residual with a high organic load to add.
- Increase the efficiency in the design process of plants for the treatment of the liquid fraction of the pig residual with a high organic load that use this technology.

By applying the new knowledge that is obtained from the results of the model, the efficiency and effectiveness of the cultivation process of the microalgae *Chlorella vulgaris* can be improved. This increases productivity per unit area and improves the removal of organic matter. Therefore, an economic impact is foreseen due to the decrease in the cost of biomass production, which could be used to obtain biofertilizers, biofuels and animal feed, and an environmental impact due to the reduction of the polluting load of the waters, residuals of the system, which allows protecting terrestrial and marine waters.

The integration of a new mechanistic model of microalgae, which includes the effect of pH on the growth rate, into the integrated model of algae and bacteria constitutes a scientific impact. This is a new contribution to knowledge, which facilitates a much better understanding of the growth process of the *Chlorella vulgaris* and a heterotrophic microbial consortium in a falling film photobioreactor.

MatLab / Simulink, version 2009b developed a program for the simulation of the growth process of the microalgae *Chlorella vulgaris.* It is a technological contribution. This allows new knowledge to be obtained, which facilitates the design of new installations of this type and the efficient operation of the system.

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IV.7.3. Lifetime prediction models of white LEDs used in lighting

Diego de los Ángeles Fernández Labrada & Miguel Castro Fernández

Abstract

The use of LEDs in lighting systems has significantly grown within recent years, and it will continue growing in the upcoming years. According to the U.S. Department of Energy reports, it is expected that 90% of the illumination market will be covered by this technology in 2025, and around 100% in 2035. This global trend has also reached Cuba. The Ministry of Energy and Mining (MINEM), for example, has outlined a strategy to place, in a progressive way, LED lighting in residential and non-residential areas. The lifetime prediction of LEDs constitutes a topic of vital importance and a challenge for the international scientific community, as the traditional failure detection methods, frequently used in traditional lighting sources, cannot be applied to LEDs due to the fact that they degrade continually. The values of performance indicators (luminous flux, colour coordinates, etc.) eventually vary till they reach levels that constitute failures. The failure modes and mechanisms are very complex in LEDs. For these reasons it is of vital importance to make contributions to the current lifetime prediction models of White LEDs used in lighting, concerning failure modes and mechanisms and performance indicators that they consider, as well as to get lifetime prediction models of White LEDs used in lighting that integrate D-D models and PoF models.

Introduction

LEDs as sources of lighting offer great advantages over traditional technologies. These advantages include high luminous intensity, the efficacy of 150 lm/W, longer lifetime (higher to 50 000 h), low power consumption, instantaneous switch-on, small weight and size, mercury-free content, controllable colour performance, good vibration resistance and low maintenance costs (Khanna, 2014; Lasance and Poppe, 2014).

For all these reasons the use of LEDs in lighting systems has significantly grown in the last years, and it will continue growing in the coming years. According to the U.S. Department of Energy reports, it is expected that 90% of the illumination market will be covered by this technology in 2025, and around 100% in 2035 (Penning et al., 2016). In Cuba, it has been introduced too. The MINEM, for example, has outlined a strategy to place, in a progressive way, LED lighting in residential and non-residential areas.

With the increase of LEDs in lighting systems, the lifetime prediction of them constitutes a topic of vital importance and a challenge for the international scientific community, as the traditional failure detection methods, frequently used in traditional lighting sources, cannot be applied to LEDs due to the fact that they degrade continually, why the values of performance indicators (luminous flux, colour coordinates, etc.) eventually vary till they reach levels that constitute failures, that is, the failure modes and mechanisms are very complex in the LEDs. Besides, due to the permanent introduction of new processes and materials in the LED lighting industry, unknown failure modes are appearing. For that reason, the lifetime modelling of LEDs has become a key issue of research in the solid-state lighting field (SSL) (Vos, den Breeijen, and van Driel, 2018).

It was also found, in the literature consulted, that the lifetime prediction models of LEDs are being developed. It includes physics-of-failure (PoF) models (Xi Yang et al., 2017) and data-driven (D-D) models such as statistical regression models (Qu et al., 2017) neural networks (Song and Qian, 2017), Bayesian networks (Lall, Wei, and Sakalaukus, 2015), Kalman filters (Lall and Wei, 2015) and particle filters (Ruknudeen and Asokan, 2017).

In theory, the PoF models are more accurate than the D-D models. However, as degradation LED lumen maintenance and chromaticity may be caused by multiple failure modes and mechanisms (chip degradation, encapsulant degradation, and phosphor degradation, etc.). Thus to make a true degradation profile it might turn out to be fairly complicated. The D-D models as they are black-box models do not require special failure models or the knowledge of a specific failure. They are not easy to be applied due to a lack of efficient procedures to obtain the necessary data to train the models, due to the inevitable mistakes in measurements and noise signals, which may affect the accuracy of predictions. Another disadvantage of the D-D models is that failure mechanisms cannot be distinguished.

For the above-mentioned, it can be said, that for industry, consumers, and scientific community, in the lighting sector, all over the world and in Cuba, it is of vital importance to make contributions to the current lifetime prediction models of White LEDs used in lighting, concerning failure modes and mechanisms and performance indicators that they consider, as well as to get lifetime prediction models of White LEDs used in lighting that integrate D-D models and PoF models.

Street lighting with a photovoltaic panel

Research Problem

The few lifetime prediction models of White LEDs used in lighting present limitations as they do not integrate the physics-of-failure (PoF) models and data-driven (D-D) models.

Research general objective

To obtain lifetime models of white LEDs used in lighting that integrate physics-based (PoF) models and data-driven (D-D) models.

Preliminary hypothesis

The analysis and evaluation of white LEDs parameters submitted to accelerated testing would allow getting lifetime prediction models that surpass the limitations of the present-day models.

Expected results

Theoretical:

- Analysis of the PoF and D-D models to predict the lifetime of white LEDs used in lighting.
- New PoF and D-D models to predict the lifetime of white LEDs used in lighting.
- Lifetime prediction models of White LEDs used in lighting that integrates D-D models and PoF models.

Practical:

- Characterization of white LEDs through measurements that allows the analysis of the failure modes and mechanisms and the performance indicators.
- Application of the proposed models to luminaires testing laboratories

The current and scientific novelty

- Attainment and validation of new PoF and D-D models that incorporate failure modes and mechanisms and performance indicators that do not consider the current models.
- Development of lifetime prediction models of white LEDs used in lighting that integrate PoF and D-D models.

Economics, social and environmental impacts of the research work

The importance of these results lies in the fact that the massive introduction of luminaires with LED technology brings with the need to ensure that, both on the side of purchases made abroad, as well as those in which they are produced at the border, meet the requested requirements from the point of view of their long life. Ttheir suppliers and/or producers propose this as one of the greatest advantages they have concerning other types of luminaires.

The operating conditions of these luminaires in national territory are very different from those in other regions not only due to the characteristics of the electrical system to which they will be connected, whether at a residential or industrial level or on streets and/or avenues (parks, sports facilities, etc.) but because of the environmental conditions to which they will be subjected.
The modelling of possible failures for the prediction of the lifetime of the different LED technologies, would allow having a way to quickly evaluate decisions by managers as to what type of technology to buy and/or prioritize based on its use.

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IV.7.4. Methodology for the dimensioning and optimal location of photovoltaic systems (PVS) with evolutionary algorithms

Adrian Romeu Ramos & Miguel Castro Fernández

Abstract

The research focuses on the development of a methodology for the design and placement of grid-connected PVS, guaranteeing the minimum costs and greatest benefits over time, taking into account the risks present in these facilities, adapted to Cuban conditions. Based on the available information, as well as the possibility that the National Electro-energy System (NES) may have a high penetration of RES, mainly PVS and require greater participation of this technology in the system control, technical and environmental restrictions will be analyzed. Regarding the design, details of the generator, wiring and inverters will be defined. The most feasible variant will be obtained from the technical, economic and environmental points of view. A computational tool will be developed to optimize the process.

Introduction

In the world, various methodologies have been implemented that allow the process of dimensioning and location of PVS to be developed. However, they lack a comprehensive analysis, which takes into account a group of factors that affect these systems, from design to the end of their useful life. Therefore, the search for optimal solutions would significantly help in decision-making for PV investments. In general, the applied methodologies are based on the following aspects:

- Designs focused on natural and social conditions (Díaz, 2003).
- Design techniques based on the combined analysis of hierarchical approaches with nonlinear programming. The objectives, in this case, are to find the point of operation with minimum costs and the maximum energy generated. Designs focused only on the geometric optimization of the installation. In this, variables such as shadow effects, terrain slope, height above sea level, and the characteristics of the equipment, among others, are taken into account (Fahmy, 1993).
- Design focused solely on the geometric optimization of the installation (Weinstock and Appelbaum, 2004).
- Location focused on climatological, environmental, orographic and legal criteria (Arán, 2008).
- Optimal oversizing of the installation to achieve the minimum cost of the energy produced (Kornelakis and Koutroulis, 2009).
- Location and design of PVS minimizing investment costs and maximizing the profitability of the project (Fernández, 2011).

- Design focused on cost, available useful area and demanded power (Díaz Santos et al., 2012).
- Designs focused on the efficiency of the proposed equipment and the benefit/cost ratio (Lorente, 2013).
- Location focused on obtaining minimum pé losses of power and energy (Rodríguez, 2014).
- Designs based on load power and availability of solar resources (Silva, 2015).
- Design focused on training neural networks from data from existing facilities (Gero, 2015).
- Focused design on levelled minimum cost (Goss, 2015).
- Design based on the optimization of technical parameters of the proposed (Hassan and A. Elbaset, 2015).
- Risk-centred design (Guerrero-Liquet, 2016).

In this sense, if all the variables that affect each of the stages of the investment process of PVS are evaluated and integrated into a methodology that characterizes the process of dimensioning and location of the photovoltaic systems, taking into account multiple objectives and applying evolutionary algorithms as an optimization tool and get a methodology that allows obtaining the best investment option for these systems, forms better results in the efficiency of its operation and exploitation.

To fulfil the proposed objective, various tasks will be carried out:

- Characterization and evaluation of PVS connected to grid in Cuba, by type and region.
- Analyze all the variables that affect the sizing and location process of photovoltaic systems.
- Include the technical - economic - environmental evaluation of PV investments in a determined time horizon within the optimization process.
- Evaluate the impact of the inclusion of risk analysis, as part of the optimization process.
- Analyze optimization methods with multiple objectives.
- Develop a methodology suitable for the design and location of PVS, based on optimization with multiple objectives.
- Obtain a programming algorithm and develop a computational tool.
- Carry out a comparative analysis between the current locations and dimensions of the grid-connected PV installations up to the end of 2019 and those offered by the software, from the point of view of the installation's efficiency coefficients: generator productivity, final productivity, capacity factor and performance factor or coefficient.

Research problem

One of the issues is the limited capabilities of the existing methodologies for the optimization of the location as well as the design of photovoltaic systems based on multiple objectives. A procedure for the location and design of such systems in Cuba that prevents obtaining the expected efficiency in them can also be considered a problem.

Expected results

It is expected that this research forms a methodology supported in a computational tool that allows for the best variant of investment in PVS taking into account multiple objectives (technical, economic, environmental is, risks and efficiency).

Solar power plant, Abel Santamaría, Santiago de Cuba

Novelty

The novelty of this research lies in obtaining a methodology (which includes a computer tool) that characterizes the location and sizing process of grid-connected PVS, taking into account multiple factors that affect: costs, profitability, useful lifetime, availability, maintainability, risks and others that guarantee the feasibility of photovoltaic investments. This research also aims to obtain efficiency levels appropriate to Cuban conditions.

Social, Economic and Environmental Importance

The depletion of fossil resources and the growing global pollution increases the need for the accelerated development of renewable energy sources (García, 2013). To achieve the implementation of PVS globally, it is necessary to increase their profitability and improve their competitiveness (Collado, 2009) This issue is of vital importance to Cuba, where the Government has planned large investments with the objective of changing the energy mix, giving greater weight to renewable energy sources, and within these to PV technology. Based on the foregoing, this work will contribute to the decision-making of investors of the Directorate of Renewable Sources of Energy pertaining to the Electrical Union, the entity that has the task of reducing fuel consumption for electricity generation. Making the best decisions regarding the location and sizing of the PV power plants will have a direct impact on Cuban society to decrease dependence on the international energy market, so the country may also have greater financial resources to use in other vital lines for economic and social development. On the other hand, the application of this methodology should improve the efficiencies of new investments, as well as the quality indicators of the energy served, at the same time that by reducing fuel consumption, the polluting charge to the atmosphere is mitigated and thus as contributes to developing sustainable of the Cuban society.

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IV.7.5. Effect of dust accumulation on the performance of photovoltaic modules installed in the mining and industrial environments

Liomnis Osorio Laurencio & Reineris Montero Laurencio

Abstract

Photovoltaic systems have increased their use in recent years at an accelerated rate. The environments where these systems are used to generate electricity are diverse. There are many factors that affect the efficiency of solar modules, these depend on the installation conditions and the geographical characteristics of the environment. In the scientific literature, there is insufficient research to study the effect of dust accumulation, which combines various dusty environments. This research exposes the problem of the effect of dust accumulation on the efficiency of photovoltaic modules, in the mining and industrial environment of the municipality of Moa, where all nickel production in Cuba is developed. The contributions of this research have a positive impact on the sizing of photovoltaic systems for this type of environment.

Background

Electricity generation systems based on renewable energy sources have had an accelerated increase in recent years. Among them, photovoltaic systems have grown a lot due to their low cost of installation and maintenance (Kawamoto, 2020). A photovoltaic module is made up of a set of interconnected cells, an encapsulant, bypass diodes, connectors, a tempered glass to protect the front and a polymer film on the back (Ndiaye et al., 2013).

Photovoltaic modules are designed for use in outdoor conditions, such as marine environments, arctic, tropical and desert. The choice of the type of photovoltaic material can have a relevant effect on the electrical and mechanical characteristics, which has an effect on the performance of the photovoltaic system (Meral and Dinçer, 2011).

Therefore, it is advisable to properly install photovoltaic modules, in order to extend their life. Over the years, the modules suffer a degradation that affects their maximum power; this value may vary in each module, as indicated in the technical sheet. In addition, there are other factors that affect the performance of photovoltaic systems.

Factors that affect the efficiency of photovoltaic modules

Environmental factors that affect efficiency include temperature, irradiance, humidity, wind speed and direction, and atmospheric pressure. Some of these factors improve efficiency, while others make it worse. Another external factor that significantly influences the performance of the modules is dust.

Solid particles whose diameter is below 500 μm are considered dust (Kumar Tripathi, Murthy, and Aruna, 2016). There are numerous studies that analyze the effect of different types of dust or dusty environments on the performance of photovoltaic panels. Among the most studied powders are red soil, cement, limestone rock, ash, coal, calcium carbonate, sand and sand-clay (Chaichan and Kazem, 2017; Maghami et al., 2016; Saidan et al., 2016).

Factors influencing dust accumulation

Numerous researches analyze the factors that influence dust accumulation and the effect they have on the performance of photovoltaic modules (Maghami et al., 2016; Saravanan and Darvekar, 2018; Zaihidee et al., 2016). Some recognize two fundamental factors: dust properties and characteristics of the local environment (Maghami et al., 2016). However, other studies recognize more factors as shown in figure 1 (Mani and Pillai, 2010; Saravanan and Darvekar, 2018).

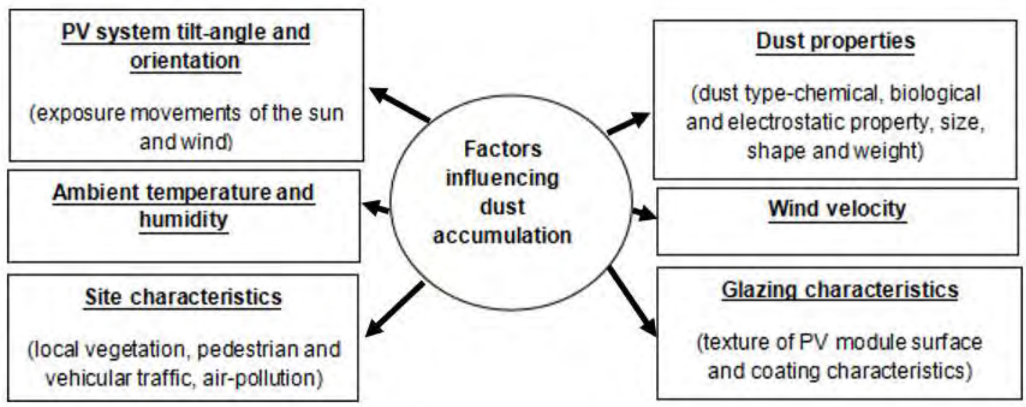

Figure 1. *Factors influencing dust accumulation (Mani and Pillai, 2010).*

These studies have shown that losses increase greatly in panels horizontally and may reach values 8-22%, while for the 45° tilt-angle losses are between 1-8%. Other observations highlight that the angle of inclination is a determining factor in the density of dust accumulation (Jiang, Lu, and Lu, 2016). The power loss is closely related to the physical and chemical properties of the powder, which can vary according to the geographical environment (Saravanan and Darvekar, 2018).

Dusty environments that affect photovoltaic modules the most

Most studies have been developed dust in desert environments, where the sand of the desert and sand storms have a strong impact on the performance of photovoltaic systems (Cordero et al., 2018; Saidan et al., 2016). There are also numerous studies on industrial or construction zones, where dust derived from materials such as cement has a negative effect on the modules. Less studied, are areas of open-pit mining, which have adopted photovoltaics for lighting areas where the mineral is extracted.

In these environments, mining activities are carried out, such as extraction, excavation, drilling and transportation, causing an increase in dust in the environment (Kumar Tripathi et al., 2016). For this reason, for each environment, it is very important to determine the cleaning methods of the solar modules, which help to improve the photovoltaic conversion.

Photovoltaic module cleaning methods

There are four ways classified to remove dust from the surface of solar panels namely natural, mechanical, electromechanical and electrostatic. More investigation and ideas are important to reduce the effect of dust (Ahmed, Kazem, and Sopian, 2013).

Emissions of nickel industry in Moa

Case study: environment mines and nickel industries in Moa

The Cubans nickel and cobalt industries are located in the Northeast area of the Holguin province, specifically in Moa city. In these areas, there are two nickel factories: Ernesto Che Guevara (ECG) and Pedro Sotto Alba (PSA), these factories that extract the laterite ore from opencast mines. the city of Moa, has a port, airport, numerous companies related to nickel and a population of 75 000 inhabitants (Riverón Zaldivar, Pacheco, and Linares, 2009).

These two industries carry out activities related to mining operations, such as drilling, excavation, cracking and transportation, which lead to an increase in dust. The combination of these activities with the fumes also emanates from different technological processes of nickel preparation, causing the entire region to be involved in a dusty environment with air pollution (gases and solids).

These factories use two different metallurgical processes 1) ECG - Ammonium Carbonate Leaching (ACL) with oil addition and 2) PSA - Sulphuric Acid Leaching (SAL). The mineral is dried at high temperatures (ACL = 11 00 °C and SAL = 600 °C) in order to obtain nickel and cobalt oxides (ACL) and sulphides (SAL). These processes generate a great volume of sub-products currently eliminated as wastes, presented in table 1. It is remarkable how much dust is expelled daily into the atmosphere.

Table 1. The volume of generated wastes in Ernesto Che Guevara (ECG) and Pedro Sotto Alba (PSA) factories (Pacheco et al., 1999).

Contaminants	SAL (PSA)	ACL (ECG)
Solid waste (t/day)	4000	1200
Liquid waste (m^3/day)	12000	
Dust emissions to the atmosphere (t/day)		10
Gases SO_2 (t/day)	16.3	17
SO_3 (t/day)	2	

In Moa, mining activities (figure 2b) and the mineral extraction process of the two factories are constant throughout the year. This causes the accumulation of dust on practically all surfaces, covering the entire region and nearby areas. Figure 2a shows the expulsion of waste in the form of gases and dust from the ECG factory. In addition, the saltpetre off the coast of Moa also provides a corrosive environment, which is why several types of adverse environments for photovoltaic systems are combined, even within a radius of several kilometres away. This problem makes Moa a region with very high air pollution (Marrero-Díaz, Cuesta-Santos, and Suárez-Benítez 2018).

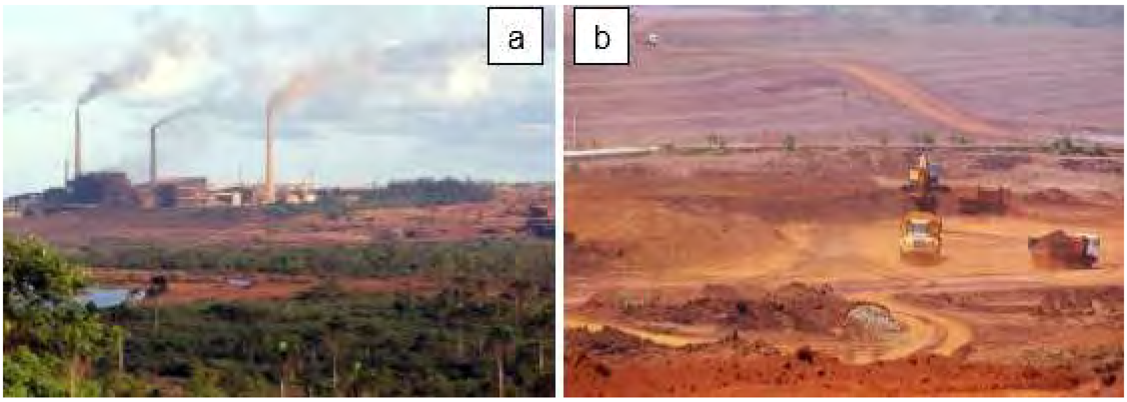

Figure 2. *Expulsion of waste into the atmosphere (ECG factory) and mining work (García Fombellida 2017; Ortiz del Toro 2019).*

Moreover, the combustion of fossils within the nickel industry causes the expulsion into the atmosphere of particulate material less than 10 microns and 2.5 (with abbreviations PM10 and PM2.5 respectively). Moa constitutes the largest emitter of this type of particle in the province, with 2 539.09 t / year of PM10 and 1 959.03 t / year of PM2.5 (Marrero-Díaz et al., 2018).

Moa climate factors

Although the Moa environment is very aggressive for photovoltaic material, the weather conditions are conducive to the development of photovoltaic solar energy. Moa has a tropical climate with an irregular seasonal distribution of rainfall, the number of days per year with rainfall greater than 1 mm is greater than 100, the annual average rainfall reaches 2,000 mm and evaporation is close to 1,600 mm. The average wind speed is 1.4 to 4.1 m / s and maintains a frequency of 180 days a year. The mean annual relative humidity for 7:30 am is 85 to 90% and for 1:00 pm it is between 70 and 75% (Retirado Mediaceja, 2012).

Current status and future plans of photovoltaic in Moa

Currently, in the Moa region, there are very few photovoltaic systems in operation. However, MINEM has plans to install photovoltaic systems integrated into the rooftops of some local companies and also in family homes. Therefore, it is necessary to carry out studies such as this, which help to size and install the solar modules, so that the energy generated is optimized. In addition, it is necessary to apply good practices to extend the useful life of solar modules, in this environment that is very different from the other municipalities of Cuba. In this environment, it is of great importance to determine the frequency of maintenance and cleaning of the modules, due to the economic costs involved.

Research problem

Insufficient knowledge of the effect of dust accumulation on the performance of photovoltaic panels, which limits the mathematical modelling of the degradation of its electrical parameters over time, and the determination of maintenance periods, for exposures near mines and Moa nickel industries.

Novelty

The determination of a coefficient that characterizes the dynamics of dust accumulation on the collecting surface of silicon photovoltaic modules, exposed to areas near the mines and nickel-producing industries in Moa, in order to improve the location of the photovoltaic system and the orientation, inclination and frequency of cleaning of the modules, in order to maximize the production of electrical energy.

Importance: social, economic, environmental

The results of this research would help improve scientific-technical actions that contribute to improving the sizing of photovoltaic systems, so as to optimize the capture of solar energy in environments with high atmospheric pollution, as is the case in the Moa. It could also help solar energy specialists to take into account maintenance cycles in this type of environment and others similar, to extend the life of photovoltaic modules.

The MINEM has the challenge of changing the country's energy matrix, in order to generate 24% of electrical energy, using renewable sources of energy (Díaz Santos et al., 2018). To contribute to this objective, there is an installation plan of 700 MWp of photovoltaic power by 2030. It is for this reason that it is important to determine an adequate cleaning cycle for solar modules, which would significantly improve the production of photovoltaic solar energy, obtaining large economic benefits. With the advent of photovoltaic installations, emissions of harmful gases to the environment from thermoelectric plants in the country are reduced. This would have a positive impact in the region where air pollution has the highest values in Cuba.

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IV.7.6. Maximum power point tracking using artificial intelligence technique in photovoltaic systems

David Díaz Martínez, Luis Vázquez Seisdedos & Rafael Trujillo Codorniu

Abstract

Among renewable energy sources, solar energy is the most used and promising alternative. In Photovoltaics (PV) the amount of electric power generated by, solar arrays changes continuously with weather conditions. Most of all, the performance of a PV array is affected by temperature, solar insolation and shading. Often the PV array gets shadowed, completely or partially, bypassing clouds, neighbouring buildings and trees, especially in large PV installations. Under uniform insolation, there is only one maximum point in the power-voltage (P-V) curve. Under partially shaded conditions, the P-V curve becomes more complex with multiple peaks. Most of the Maximum Power Point Tracking (MPPT) techniques track well the MPP under zero-shading conditions, however, when Partial Shade Condition (PSC) occurs, these methods are trapped at a local maximum which significantly reduces the efficiency of the PV system. In this work, we propose a new MPPT technique based on Particle Swarm Optimization (PSO) for improving the performance of the controller facing PSC conditions.

Introduction - background

Demand for electrical energy has remarkably increased during the last decades with a growing population and industrial progress. For a long time, fossil fuels have served as the major source of generating electrical energy. Recent years' overexploitation and consumption have brought the energy crisis to the modern world (Yang et al., 2019). Awareness of environmental protection and sustainability in the burning of fossil fuel and its products as the primary energy source is also arising. In the next few years, the world is supposed to face several problems related to the exhaustion of some energy sources (Vazquez et al., 2018), mainly those regarding fossil fuels. It is also well known that some aspects concerning the increase of oil price due to economic and political questions have been the cause of the economic crisis in the last decades. The search for renewable energy sources then becomes more and more intense as a prominent alternative for the mitigation of the world energy crisis. Many environment researchers and organizations advocated energy conservation and carbon dioxide (CO_2) reduction for the well-being of earth creatures and humans as well. Many alternatives for energy, such as energy generated from geothermal, solar, tidal, wind, and waste (Eltamaly and Abdelaziz, 2012), are suggested. Among these, solar energy is the most used and promising alternative energy with a fast-growing energy market share in the world's energy industry due to the following advantages.

-Sunlight is inexhaustible and is easy to access for its irradiance covering most of the land.

-There is no noise or pollution in the generation of solar energy.

-Solar energy is considered safe energy without burning any material.

-Solar cells are ideal energy generators that require no fuel, generate no emissions, have no moving parts, can be made in any size or shape, and rely on a virtually limitless energy source, namely, the sun.

The significant cost reduction of photovoltaics (PV) modules in the last few years have made the use of solar energy particularly attractive. The number of PV system installations are becoming bigger every year. Falling system prices have been a key driver of this recent growth and competitiveness, but reduced costs are only one part of the equation for long-term profitability. Maximizing power output over its lifetime is critical to lowering the cost of electricity and maximizing investment returns (Gosumbonggot and Fujita, 2019).

The photoelectric effect occurs when a beam of ultraviolet light, composed of photons, strikes one part of a pair of negatively charged metal plates. This causes electrons to be “liberated” from the negatively charged plate. These free electrons are then attracted to the other plate by electrostatic forces. This flowing of electrons is an electrical current. This electron flow can be gathered in the form of a direct current (DC). This DC can then be converted into alternating current (AC), which is the primary form of electrical current in electrical power systems. PV devices take advantage of the fact that the energy in sunlight will free electrical charge carriers in certain materials when sunlight strikes those materials. This freeing of electrical charge makes it possible to capture light energy as an electrical current (Chin, Salam, and Ishaque, 2015).

Unfortunately, PV generation systems have two major problems: the conversion efficiency of electric power generation is very low (9-16%), especially under low irradiation conditions and the amount of electric power generated by solar arrays changes continuously with weather conditions. The main reason for the low electrical efficiency of a PV array is the nonlinear current-voltage (I-V) and power-voltage (P-V) characteristics of PV arrays and the effects of environmental conditions on these characteristics such as varying temperature and different insulation levels (Laudani, Riganti Fulginei, and Salvini 2014).

Solar cells may be integrated to form modules or panels, and large photovoltaic arrays. The performance of a PV array system depends on the solar cell and array design quality and the operating conditions as well. The output voltage, current, and power of the PV array vary as functions of solar irradiation level, temperature, and load current (Mohapatra et al. 2017).

Generally speaking, there are four means to improve the efficiency of PV plants.

(1) increasing the photoelectric conversion efficiency of photovoltaic diode components,
(2) increasing the frequency of direct light,
(3) improving the efficiency of the inverter,
(4) improving the maximum power point tracking (MPPT) for the PV array.

The first three methods are to improve the hardware devices, is not easy as it depends on the technology available, it may require better components, which can increase drastically the cost of the installation, yet the four one is to improve the conversion efficiency by utilizing the internal software embedded in components. Improving MPPT with new control algorithms is easier, not expensive and can be done even in plants that are already in use by updating their control algorithms, which would lead to an immediate increase in PV power generation and consequently a reduction in its price.

A switch-mode power converter is used to maintain the PV array's operating point at the Maximum Power Point (MPP). An algorithm called Maximum Power Point Tracking (MPPT) does this by controlling the PV array's voltage or current independently of those of the load. If MPPT techniques are used in PV systems, can be generated more power with the same number of modules. These techniques allow the module generates its maximum power, having a high level of utilization of its generation capability. Thus, the overall system cost can be minimized (Ram, Babu, and Rajasekar 2017).

MPPT is not a mechanical tracking system that "physically moves" the modules to make the point more directly at the sun. MPPT is a fully electronic system (a controlled DC-DC converter) inserted between the PV source and the load that monitors the photovoltaic array to operate at its maximum power point (MPP) depending on the load state, PV array generation, PV cell temperature and solar radiation variations.

MPPT Methods

To date, numerous MPPT controllers have been presented and implemented in the literature, these controllers have some generic requirements such as low complexity, low cost, minimum output power fluctuation, and the ability to track quickly when operating condition changes (Tobón et al., 2017).

Among the most desirable features in MPPT techniques are the following: stability, fast dynamic response, small steady-state error, robustness to disturbances and efficiency in a large power range.

Among conventional approaches, the most dominant methods are Incremental Conductance (IC) (Kurella and Suresh, 2013), Perturb and Observe (P&O) (Ishaque, Salam, and Lauss 2014), Hill Climbing (HC) (Zhu et al., 2018), Parasitic capacitance (PC) and Constant Voltage (CV). The most widely used are (P&O) and (InC). These conventional methods achieve moderate performance with easy implementation and a low cost.

The last years have been adopted artificial intelligence (AI) techniques mainly because of their flexibility and reasoning capabilities that are useful to deal with strong non-linearities and complex systems (Kermadi and Berkouk, 2017). The most talked-about approaches are Fuzzy Logic Control (FLC) (Robles Algarín, Taborda Giraldo, and Rodríguez Álvarez, 2017), Artificial Neural Network (ANN) (Messalti, Harrag, and Loukriz, 2017) and other Computational Intelligence (CI) methods. The methods in this last category are nature-inspired computational methodologies that address complex real-world problems and can be divided into Swarm Intelligence Algorithms and Evolutionary algorithms.

The last years have been adopted artificial intelligence (AI) techniques mainly because of their flexibility and reasoning capabilities that are useful to deal with strong non-linearities and complex systems. In Fuzzy Logic Control (FLC)-based MPPT, a mathematical model for the system is not required. However, its performance depends on the rule basis, number of rules, and membership function determined by a trial and error procedure, which is time-consuming. Another well-known approach is Artificial Neural Network (ANN) where weights associated with the neurons should be accurately determined by a training process and requires large training data before the method is implemented.

Other popular MPPT´s are based on Computational Intelligence (CI) methods which are nature-inspired computational methodologies that address complex real-world problems. It can be mentioned the Particle swarm optimization (PSO) (Ishaque and Salam, 2013), Ant colony optimization (ACO) (Titri et al., 2017), Genetic algorithm (GA) (Mohamed, Berzoy, and Mohammed, 2017) and Differential evolution (DE).

Most of all, the performance of a PV array is affected by temperature, solar insolation, shading and array configuration. Often the PV array gets shadowed, completely or partially, bypassing clouds, neighbouring buildings and trees, especially on large PV installations. Under partially shaded conditions (PSC), the P-V characteristic becomes more complex with multiple peaks. Under uniform insolation, there is only one maximum point in the P-V curve (Fig. 1).

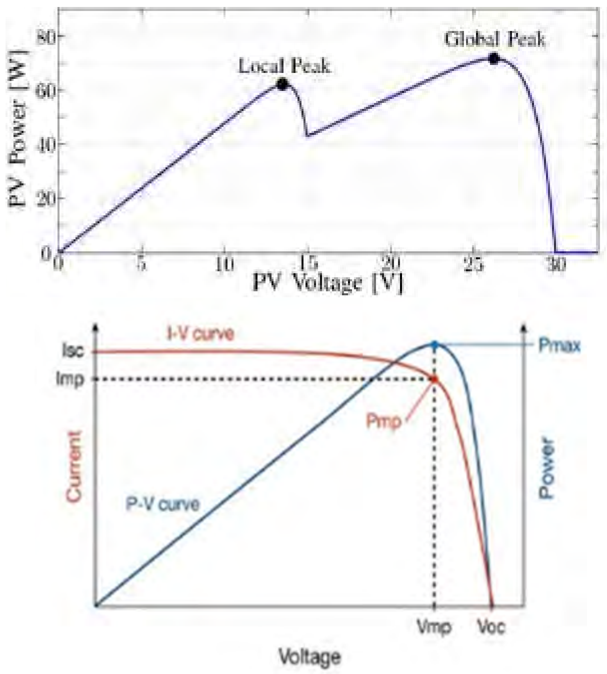

Figure 1. *Characteristic I-V and P-V curves of a PV panel. a) Under uniform irradiation. b) Under partial shading*

Conventional MPPT techniques track well the MPP under zero-shading conditions, however when PSC occurs, these methods are trapped at a local maximum which significantly reduces the efficiency of the PV system which forces the researchers to find new techniques for MPPT under PSC (Islam et al., 2018).

In this context, Particle swarm optimization (PSO) is rising as one of the most promising techniques with great potential to deal with this complex situation. PSO is independent of the characteristics of the PV system and is very simple yet it offers a great deal of flexibility to suit changing weather conditions (Eltamaly, Al-Saud, and Abo-Khalil, 2020). The proposed PV system structure is shown in Fig. 2.

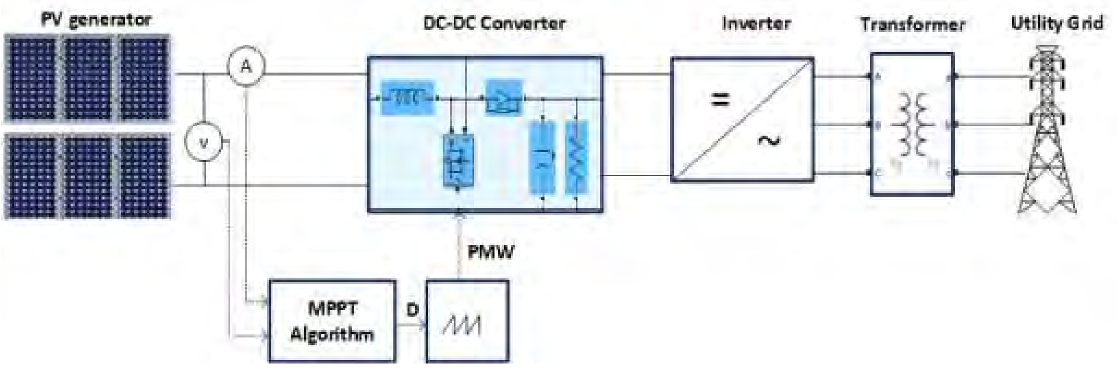

Figure 2. *Schematic diagram of PV system with MPPT controller*

Investigation problem

The low efficiency of PV system during partial shade condition (PSC) due to problems in most of the current methods for tracking the maximum power point of the PV panels in this situation of fast changes in irradiation and temperature.

Novelty

A new method based on artificial intelligence with better accuracy, minimal steady-state errors and a greater range of parameters compared with those currently used in the dynamic tracking of the maximum power point in situations of partial shading.

Importance: social, economic, environmental

By guaranteeing adequate monitoring of the maximum power point of the Photovoltaic System even in sudden changes in environmental conditions, it is guaranteed the extraction of the maximum power that the photovoltaic array is able to deliver and therefore an increase in the efficiency in its operation. That means that in every moment is been delivered more energy to the national network no matter weather conditions.

This makes the investment to be retrieved in a lower period of time. Therefore, this is a contribution that has a positive impact on the profitability and sustainability of these photovoltaic systems that are being implemented in the country. By guaranteeing photovoltaic systems that function efficiently and sustainably, the path is provided for the expansion of this type of generation in the country. By accomplishing this, it is possible to achieve the penetration levels of renewable sources of energy desired. In addition, a considerable reduction of environmental pollution would be achieved by not generating all that energy using fossil fuel.

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IV.7.7. Improvement of the energy efficiency on micro-hydropower plants in autonomous regimen controlling the frequency with AC-AC converters

Henry Bory Prevez & Luis Vázquez Seisdedos

Abstract

Most of the micro-hydropower plants, useful for electricity production in intricate regions, operate in an autonomous regimen. Therefore, it is necessary to accomplish the frequency regulation. One way to do the frequency regulation is changing the power dissipated in dump loads employing AC-AC converters. These converters have the disadvantage of consuming reactive power, contributing to aggravating the power factor at the generator output. In this research, to avoid the deterioration of the power factor is proposed a combination of two topologies of rectifiers with the symmetrical switching method. The first topology is a bridge three-phase rectifier using diodes with a serial switch with the dump load and the second one is a bridge single-phase rectifier using diodes with a serial switch with the dump load. In both cases, the switch is switched with a symmetric angle. With this proposed is improved the power factor at the generator output.

Introduction

Due to the energy crisis, it has been directed attention to the renewable sources, as shown by the papers (Bordons, García-Torres, and Valverde, 2015; García et al., 2016; López, Somolinos, and Núñez, 2014; Ortega et al., 2016; Real-Calvo et al., 2017; Singh and Singal, 2017; Wu et al., 2014) creating the named electrical microgrids that operate in island mode (Anwer, Siddiqui, and Anees, 2013; Colak et al., 2015; Farfán, Cadena, and Villa, 2015; Ortega et al., 2016; Piris-Botalla et al., 2016; Qian et al., 2013).

One type of renewable energy is hydraulic energy and in the case of Cuba is used employing micro hydropower plants (µHPPs). At this moment there are in Cuba 107 µHPPs placed mainly in provinces of the Orient region and are operating standalone (isolated from the National Electrical System). The advantages of these µHPPs give support in the very intricate rural region supplying energy to thousands of people and both social and economic objectives. It is not necessarily big water flux and they produce a low environmental impact (Bory et al., 2021; Fong Barrios et al., 2018; Peña Pupo and Fariñas Wong, 2020).

One method used to regulate frequency in these standalone µHPPs is employing an electronic load controller (ELC). Various ELCs modify the dissipated power in the dump load using alternating current /alternating current converters (AC-AC) connected in shunt with the user´s load, in such a way that the active power delivers by the generator (P_G) be constant all time. This P_G must be equal to the dissipated power by the ballast load (P_L) plus the active power consumed by the user (P_U), as shown in Figure 1a) and the balance curve in Figure 1b). The basic equation that describes this type of regulation is: $P_G = P_L + P_U$ (Kurtz et al., 2007; Win & Ze, 2015; Singh et al., 2018.

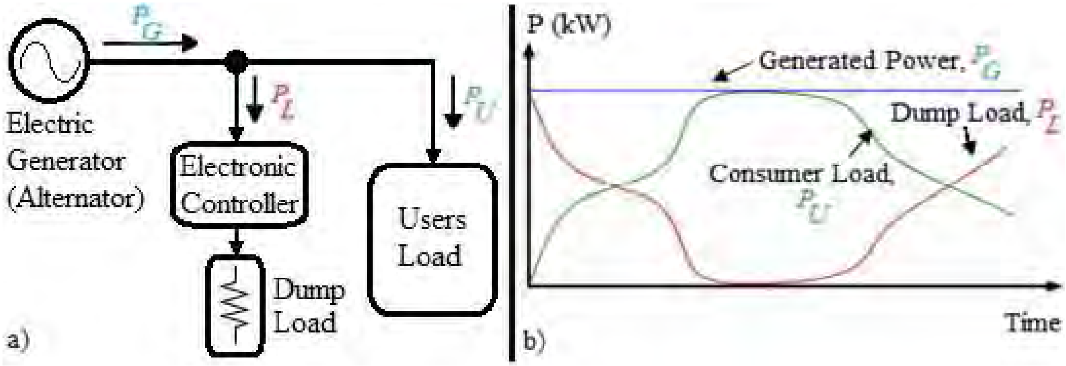

Figure 1. *The combined frequency control scheme of autonomous micro-hydropower plants.*

a) Scheme with electronic load controller. Source: (Bory et al., 2021) *Curves relating the generated power, the user´s consumption and the dump load. Source:* (Win Aung and Ya, 2015)

For the mCHs the frequency regulation by dump load has the following advantages with respect to turbine water flux control: its implementation is simpler from the electronic point of view, the lower cost, faster dynamic response for the abrupt change in the user´s load, it is more reliable. Moreover, the frequency regulation by dump load has not the water hammer problem that may have the frequency regulation by turbine water flux control (Ortega et al., 2016; Singh et al., 2018; Singh and Singal, 2017; Win Aung and Ya, 2015).

As mentioned in the previous paragraph the way of varying the dissipated power in the dump load is using the AC-AC converter. This converter is widely used as demonstrated by the following authors, Fong Barrios et al. (2018; Jiménez Pinto (2013); Kurtz and Anocibar (2007); Marín - Jimenez and Carvajal -Quintero (2015); Peña Pupo and Fariñas Wong (2020); Riaz et al. (2018); Singh et al. (2018); Win Aung and Ya (2015). It is true that the AC-AC converter is widely used due to its manufacture is very simple and cheaper with respect to another converter for this application, but its main disadvantage, that it is not considered by the authors previously mentioned in this paragraph, is the negative effect produced by the reactive power consumption of this converter at the generator output, such as the efficiency reduction and the decrement of the generator capacity with respect to current deliver. Both aspects are related to the efficiency index power factor (pf), index did not consider in the mentioned studies in this paragraph.

For that reason, arise this research.

Research problem

There are limitations with the efficiency index power factor at the output electric terminals of the generator of the mHPPs operating in autonomous regimen and regulating frequency employing the variation dump load using AC-AC converters method. This affects the human and economic development of the persons that live in the communities isolated from the national electric system.

Research purpose

The objective of this research is to propose a combination of the rectifier structure and the symmetrical switching method that varying the power dissipated in the dump load improve the efficiency index power factor at the output electric terminals of the generator of the mHPPs operating in an autonomous regimen.

Novelty

At this moment in the scientific literature related is not reported until now, the combination of the rectifier structure and the symmetrical switching method and with this improve the index power factor at the output electric terminals of the generator of the mHPPs operating in an autonomous regimen.

The authors proposed to combine two topologies of rectifiers with the switching method named symmetrical. The first topology is a bridge three-phase rectifier using diodes with a serial switch with the dump load, in which the switch is switched with a symmetrical angle, whose scheme is shown in Figure 2. This scheme will be used to control the power dissipated in the dump load and hence it will be the final action element (EAF) in the frequency regulation loop.

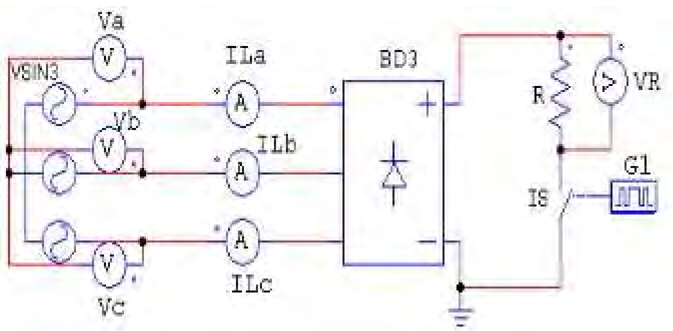

Figure 2. *Scheme of the three-phase rectifier switched with symmetrical angle, implemented in Psim®. Source:* (Bory Prevez et al., 2018)

The elements of this scheme are: three-phase sinusoidal voltage source (*VSIN*3) with frequency 60 Hz and phase to phase effective voltage 190.53 V. This source represents the electrical generator; a bridge three-phase rectifier, using diode (*BD*3); switch (*IS*) could represent an Isolated Gate Bipolar Transistor (*IGBT*) for an instant; the gating (*G*1). Its function is to apply the desired gating pulse to the switch and its parameters are frequency (360 Hz), switching point numbers (2) and switching points (angles and desired width); load resistance (*R*=4.03 Ω) that represent the dump load and the voltage and current probes (V_a, V_b, V_c, V_R, I_{La}, I_{Lb} e I_{La}) that show the instantaneous waveforms of the voltage in each phase of the electrical generator, the voltage across *R* and the current at the rectifier input terminal.

Figure 3 shows how to define the symmetrical switching method, or the same, switching with symmetrical angle. Figure 3a) presents each one line to the ground voltage of the generator and in figure 3b) the voltage across the dump load resistance. The symmetrical switching method is defined as follow, the fulfilled dots represent the natural switching points and starting any fulfilled dots it must wait for an angle of alpha degree (a) to close the switch and it must open an angle of alpha degree before the next natural switching point.

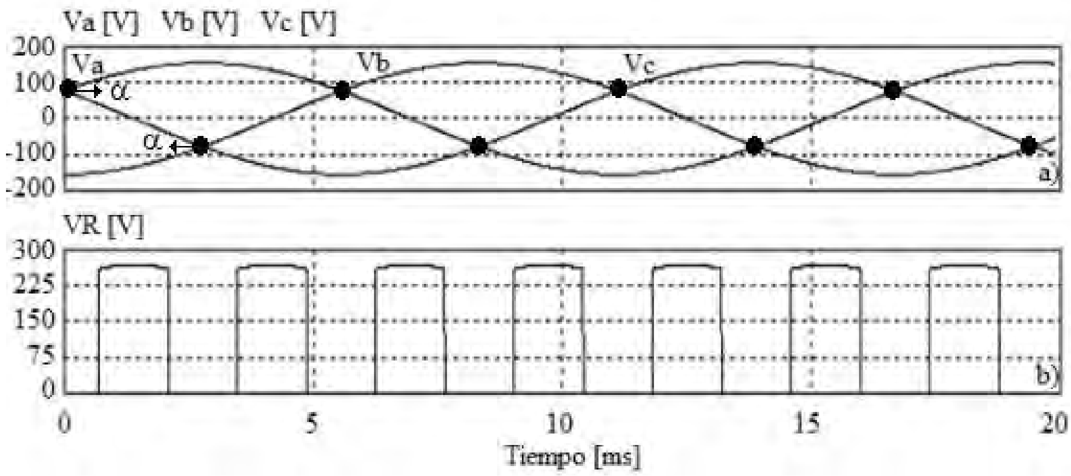

Figure 3. *Graphs of the waveform of the three-phase rectifier switched with symmetrical angle. (a) Line ground voltage at the generator output terminals, (b) Voltage across R. Source:* (Bory Prevez et al., 2018)

The second topology is a bridge single-phase rectifier using diodes with a serial switch with the dump load, in which the switch is switched with a symmetrical angle. This scheme is shown in Figure 4. This scheme will be used to control the power dissipated in the dump load and hence it will be the EAF in the frequency regulation loop.

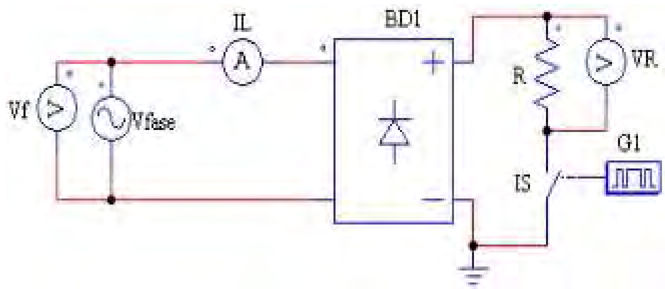

Figure 4. *Scheme of the single-phase rectifier switched with symmetrical angle, implemented in Psim®. Source:* (Bory et al., 2019)

The elements that constitute this schemes are: single-phase sinusoidal voltage source (*Vfase*) with frequency 60 Hz and effective voltage 110 V, which represents one phase of the electrical generator; bridge single-phase rectifier using diodes (*BD1*); switch (*IS*) could represent an Isolated Gate Bipolar Transistor (*IGBT*) for an instant; the gating (*G*1), its function is to apply the desired gating pulse to the switch and its parameters are frequency (120 Hz), switching point numbers (2) and switching points (angles and desired width); load resistance (*R*=4.03 Ω). That represents the

ballast load and the voltage and current probes (V_f, V_R, I_L) that show the instantaneous waveforms of the source voltage, the voltage across *R* and the current at the rectifier input.
Figure 5 shows how to define the symmetrical switching method. Figure 5a) presents one line to the ground voltage of the generator and in figure 5b) the voltage across the dump load resistance. The symmetrical switching method is defined as follow, the fulfilled dots represent the points of crosses by zero and starting of any fulfilled dots it must wait for an angle of alpha degree (a) to close the switch and it must open an angle of alpha degree before the next point of the cross by zero.

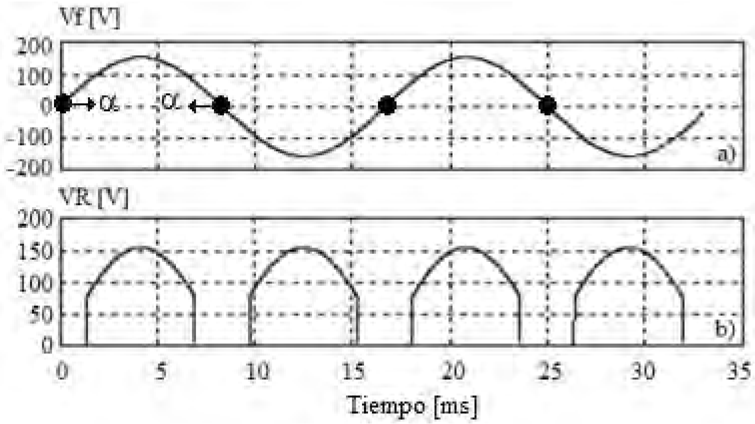

Figure 5. *Graphs of the waveform of the three-phase rectifier switched with symmetrical angle. (a) Line ground voltage at the generator output terminals, (b) Voltage across R. Source:* (Bory et al., 2019)

Importance: social, economic and environmental

From the social vision, the µHPPs are a mature renewable energy source based, being the most reliable and cost-effective renewable power generation technology available (IRENA, 2012). Its main advantage is to produce electric energy letting the development and improving the life quality of the rural community habitats where the µHPPs is installed (Jiménez Pinto, 2013; Marín -Jimenez and Carvajal -Quintero, 2015; Singh et al., 2018; Singh and Singal, 2017; Win Aung and Ya, 2015).

From the economical viewpoint, the µHPPs are a cost-competitive option for rural electrification for remote communities, due to their construction, maintenance and utilization cost is low (Jiménez Pinto, 2013; Marín -Jimenez and Carvajal -Quintero, 2015; Singh et al., 2018; Singh and Singal, 2017; Win Aung and Ya, 2015). As important information obtained of IRENA (2019; 2019b) is that more than 130 million people around the world use autonomous µHPPs as an energy source.

From the environmental point of view, the µHPPs belong to clean technology because these don´t produce air and water pollution by both CO_2 and ashes emissions. Moreover, its environmental impact is low because they do not change either the river flow regimes or the zone biodiversity where are built. (Jiménez Pinto, 2013; Marín -Jimenez and Carvajal -Quintero, 2015; Singh et al., 2018; Singh and Singal, 2017; Win Aung and Ya, 2015).

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IV.7.8. Procedure for the efficient operation of fuel oil genset systems

Aliniuska Noa Ramírez, Reineris Montero Laurencio, Arístides Alejandro Legrá Lobaina & Yiezenia Rosario Ferrer

Abstract

This paper presents the main characteristics and factors related to the availability of electric power. This general approach analyzes the availability problem for the planning of the short-term operation of fuel oil gensets and the satisfaction of the electricity demand. Supervised and unsupervised learning methods and techniques of data mining are proposed for: 1) the analysis of historical data, 2) the collection of the information that is implicit in the variables that represent the different operating states and 3) the extraction of the knowledge that is contained in the relationships between the values of the different attributes or characteristics present in the operational variables that make up the operating decisions. This is done through a procedure that considers: 1) the characterization of the values of the performance indicators, 2) the use of data mining techniques and methods, 3) the application of predictive modelling, 4) artificial intelligence techniques and methods, and 5) the obtaining of a set of variants that satisfy the requested demand using the linear programming method, a generalized efficiency indicator corresponding to the most efficient operating variant is minimized.

Background

The prediction of electric power production is a transcendental process in the planning of the electric industry. It is vital in the management of energy service systems, as well as in the projection of the availability of electric energy in power plants. The general problem facing any power plant that manages electrical energy for a socio-economic environment is to efficiently meet the electricity demand. First and foremost, this problem leads to the characterization of the availability of electrical energy and its demand. These are fundamental factors for the planning of the operation of power plants in certain time horizons.

Availability of electric energy is defined as the security of producing power at full capacity at the precise moment when the load dispatch demands it. It is established through the relationship between the time in which the generation units are available to operate and the time required for operation, and it is a critical indicator that allows evaluating the operational performance of the power plants. The Institute of Electrical and Electronics Engineers (IEEE) in the IEEE 762 standard establishes specific criteria for availability and capacity, as well as technical indicators of performance and quality of the energy supplied, all of them for a given period (IEEE, 2006).

The most recommended indicators for the evaluation of performance in energy systems are: the availability factor, the equivalent availability factor and the equivalent rate of forced outages (Curley, 2006). The analysis of these factors is fundamental in decision making for the operation and the development of maintenance strategies of any power plant since they allow determining the operating costs of the generating units that make up a power plant.

It is important to highlight that the current diversification of energy systems, and in particular, the impacts of the penetration of distributed generation (DG) systems in electricity grids. Their insertion in the energy mix of countries (Rubiños Jiménez, 2015; Singh and Sharma, 2017), have caused a strategic change in the planning (Bordons, García-Torres, and Valverde, 2015) of economic offices operating both in centralized or liberalized regulatory frameworks (Lozano, Luyo, and Molina 2018).

In the liberalized environment, Wholesale Electricity Market, the figure of the central operator disappears. In the economic dispatch, the supply of electric power is decided based on power purchase and sale offers made by market agents or through physical bilateral contracts between producers or external agents and qualified consumers (Lozano et al., 2018). In the case of a centralized framework in the economic dispatch, there is a central operator who decides the operation of each generating station or plant daily (and of each generation unit within a plant). This is to guarantee the electricity demand for the whole year, with the minimum operating cost for the production of power and the supply with minimum losses of the generated power to the loads. It is subjecting to the technical and load restrictions and taking into account the availability of energy resources and transportation (Grainger and Stevenson, 1996). It should be noted that, as there are no exactly equal dispatches, each electric system establishes its own criteria, methods and prediction models suitable for planning the operation of DG systems. The decision support tools are different and are the result of the local energy needs.

In its most general conception, the IEEE refers to DG as: the production of electricity with generating units that are sufficiently small in relation to large generating plants so that they can be connected almost anywhere in an electrical system (Ackermann, Andersson, and Söder, 2001; Pepermans et al., 2005). The trend internationally has been to analyze the impact of DG systems on electricity systems (Segura Heras, 2005). This is to develop policies and regulations aimed at reducing greenhouse gas emissions, using energy rationally and efficiently, and assessing the penetration of renewable energy sources (IAEA, 2009).

Renewable energies (hydro, wind, solar, bioenergy) are distributed all over the planet and the heterogeneous characteristics of their flows allow decentralized production and collection of electrical energy. Among the renewable DG technologies are: wind turbines, solar photovoltaic and thermal, mini-hydro, geothermal, tidal and fuel cells. The use of these technologies depends on the particular requirements of the electro-energy system to be fed. They are used for: supporting the distribution network, energy storage, remote or isolated generation, or baseload or peak load generation. Since not all countries have convenient renewable sources in their territory that can provide electricity, they have also selected DG technologies that use non-renewable sources such as: cogeneration, gas turbines, microturbines and internal combustion engines.

In Cuba, the technologies with the greatest participation in DG are internal combustion engines, used as the primary machine in generator set (GE) systems. In 2005, through the Energy Revolution programs (Arrastia Avila, 2017) they were introduced to the national electric power system (SEN) and it is the DG system with the greatest energy impact. These systems are used for base load and peak load generation, with a total of 2512 GW of installed capacity and a generation of 3962.4 GWh per year (ONEI, 2020). For this reason, in the Guideline 242 of the Economic and Social Policy of the Party and the Revolution in Cuba (PCC, 2011), emphasizes that special attention should be devoted to maintenance and to achieve high availability rates in generator sets.

Among the generating sets currently operating in the country, are the emergency ones, which are located based on economic and social objectives. They are generally expected to operate in situations of lack of electricity and without connection to SEN. There are also isolated diesel generator sets; batteries of diesel generator sets; distributed fuel oil generator sets; and fuel oil power plants (CEFO, Spanish acronym) made up of several fuel oil generator sets (GEFO, Spanish acronym) with the same technological and operational characteristics.

CEFOs are the plants with the largest installed capacity. They are located near electrical substations for their link with the SEN. They are used together with thermoelectric power plants in frequency regulation, increasing reliability in the SEN (Martín, 2010) and their operation is normally planned in a stable work regime as base load generation. They supply electrical energy continuously, they operate in parallel with the distribution network and use the centralized electrical power system (SEP) network for backup and maintenance (Aguila, 2012). The CEFO with the largest installed capacity in the country is located in the municipality of Moa. It has a SCADA (Supervisory Control And Data Acquisition) supervision and control system that performs, among other functions, the generation of reports on the data of operational variables.

On the other hand, the entry into operation of the CEFOs increased the availability of power, which is centrally managed by the National Load Dispatch (DNC, Spanish acronym) to meet the maximum electricity demand. This availability is evaluated through, among other aspects, the available power factor (Hernández Montero et al., 2018). This factor is estimated in hourly intervals ranging from 1 hour to 24 hours is, therefore, a time horizon belonging to the short term.

This indicator is used to plan the operation of the GEFOs that make operational decisions in correspondence with the guidelines at each dispatch level (provincial, territorial and national) and specifically in the operational load dispatch (DCO, Spanish acronym) of each power plant. These decisions are characterized by being unilateral and do not allow the generation of new knowledge (patterns) that guarantee a space of compatibility between dispatches.

In a DCO, in order to make adequate operating decisions, these must be based on a process of informative and gnoseological analysis of the historical operating data of the GEFOs. However, due to the operational dynamics of the plants, the DCO operators-decision makers do not have enough time or tools to convert this data into information that would allow them to generate the values of the indicators that characterize the best operational performance of the GEFOs.

In general terms, the operational decisions of a DCO are based on the following factors: the operation recorded through measurements up to the present time and the integration guidelines with the economic dispatches. The integration of these factors leads to the fact that the operation decisions, in the best scenario, should consider predictions focused on availability performance indicators, benefiting the decision making for the planning of the operation of the groups.

The problem of electrical energy availability for planning the short-term operation of M fuel oil gensets can be described as follows: How to determine the load level (K_i) of each of the GEFO to be operated in order to satisfy the electricity demand? To solve this, it is necessary to know each GEFOi (i=1;2;...;M): the nominal powers (Pni); the technological and operation restrictions in the stable operation regime; the permissible values of the operational variables and the behaviour of the historical operation decisions. Predictive models generate performance indicators and the formalization of a generalized efficiency indicator for each GEFOi and for the CEFO.

The general approach considered in this research is based on the premise that the operators-deciders of the DCOs are related to the different methods of information analysis. This allows us to study the relationships between the historical numerical data of the monitored operational variables and thus, to determine patterns in the behaviour of the historical operating decisions. These patterns will formalize predictions (by means of the model) leading to performance indicators and a procedure based on availability can be executed according to the specific situation. Therefore, the correct execution of a procedure for these purposes will depend on the decision-makers who:

- Have knowledge about the relationships between the data of the monitored variables and patterns in the historical operation decisions to obtain, by means of predictive models, the values of the performance indicators of the available GEFOs, considering their technological and operational constraints of the stable operation regime.
- Have a set of feasible variants of GEFO operation complying with the performance indicators.
- Decide from the values of the feasible variants, the most efficient solutions that can minimize a generalized efficiency indicator.

In summary, the present work highlights that the planning of the short-term operation of a fuel oil power plant can be improved. This can be done based on the values of its performance indicators, which allow recognizing the variants that satisfy the requested demand and among them selecting the most efficient ones, through predictive modelling. This aspect has not been adequately valued in the research developed in these systems, due to the complexity involved in obtaining models from a predictive and historical operative approach in fuel oil gensets power plants. A model with these characteristics has never been integrated into a procedure for this purpose.

Although there have been published works that address GE modelling, research has been mainly directed to the study of: operational efficiency, operational variables and performance indicators, technical condition analysis and availability and reliability in the national level (Alonso Preciado and Suárez Piña, 2011; de Armas Teyra, Gómez Sarduy, and Viego Felipe, 2012; Bermúdez and del Río, 2015; Castillo Cobas, Febles Rodríguez, and Fernández, 2011; Castro Álvarez, Pérez Pérez, and Bravo Amarante, 2015; Castro, Money, and Leizan, 2018; Corrales Barrios and Ramírez Vázquez, 2013; Hidalgo Batista, Rigol Cardona, and Batista Rodríguez, 2009; Hourné Calzada et al., 2012; de la Fé Dotres, Domínguez Fontanil, and Sierra, 2010; de la Fé Dotres and Jaime García, 2012; Montero Laurencio, Reyes, and Marisma, 2008; Pérez Bicet, 2012). None of these investigations has considered modelling with the objective of formalizing predictions derived from the patterns implicit in the historical operating decisions of GEFOs.

At the international level, the literature consulted has shown that modelling is one of the most recurrent lines of research in terms of electric power production prediction (Hammad et al., 2020; Suganthi and Samuel, 2012). The development achieved in the models used in prediction in the short term have favoured the use of machine learning and models based on artificial intelligence such as: artificial neural networks, support vector machines and fuzzy logic, as reported in the literature (Singh and Sharma 2017).

Certainly, the development of these models has allowed new hybrid DG systems to be designed that efficiently combine diesel generators and wind turbines and others that also use photovoltaic systems. Novel architectures have been developed for energy management in micro-grids involving diesel gensets and isolated or emergency operation of gensets and monitoring systems have been studied (Best et al., 2007; Celli et al., 2005; Katiraei and Iravani, 2006; McArthur et al., 2005; Sebastian, 2009; Wies et al., 2005). However, there are few studies that address predictive modelling to generate the indicators that determine the best operational performance in fuel oil genset power plants.

The development of a predictive model in gensets is a very difficult task due to the computational complexity that involves the prediction of electrical variables with very fast dynamics in relation to very large time constants of mechanical variables (Hill, Zanchetta, and Bozhko, 2012; Leuchter et al., 2006).

It is necessary to apply supervised and unsupervised learning methods and techniques of Data Mining (DM) for the analysis of historical data of operational variables to contribute through predictive modelling and to improve planning in the short-term operation of a CEFO. It is also necessary to collect the information implicit in the historical operating decisions that represent the different operating states in the steady-state and extract the knowledge contained in the relationships between the values of the different attributes or characteristics of the operational variables that make up the historical operating decisions analyzed (Hernández O., Ferri R., and Ramírez Q., 2018; McArthur et al., 2005).

Since the GEFOs have common operational and technological characteristics, which creates the possibility for group analysis, the benchmarking process is used to compare and evaluate the patterns contained in the historical operating decisions. From these patterns and through a predictive model based on machine learning, performance indicators that characterize the availability are estimated. This allows operational decision making that focuses on the best operational performance.

With the values of the performance indicators reached and through the use of a suitable computer system, it will be possible to optimize a generalized efficiency indicator applying the linear programming method, to effectively and efficiently plan the short term operation of the GEFO. Finally, a procedure that adequately integrates the results obtained will be developed.

Based on the above arguments, the following scientific problem is inferred as a scientific problem: the need to improve the short-term operation planning of a fuel oil power plant that, based on the values of its performance indicators, allows recognizing the variants that meet the requested demand and selecting the most efficient among them.
It is assumed that a procedure that guarantees correct planning of the short-term operation of a fuel oil power plant must consider:

- Characterize the values of the performance indicators: the use of data mining techniques and methods for regularization and clustering and the application of predictive modelling random forest.
- Obtain the set of variants that satisfy the requested demand (feasible) use the Simplex Method of linear programming.
- Obtain the most efficient variants, the generalized efficiency indicator must be minimized using artificial intelligence techniques and methods.

Then, the scientific novelty that frames all these aspects is based on a procedure for the planning of the short-term operation of a fuel oil power plant that, based on its performance indicators, lists the feasible variants and selects the most efficient among them.

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IV.7.9. Increase of electricity quality and wáter savings in autonomous micro-hydropower through a combined flow-dump load control procedure

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Abstract

Frequency regulation in isolated power generation is a great challenge, especially in micro-hydropower where power capacity is very small. This research proposes a frequency control procedure for autonomous micro-hydropower by a combined method of flow control in hydraulic turbines with dump load control. The proposed procedure must comply with Cuban standard NC62-04, designed for connected power generation plants. This procedure takes advantage of the advantages of both methods separately and reduces the resistive dump load, allowing an increase in the use of the primary energy resource and energy production. The state of the art of frequency regulation by flow and load controls is presented, as well as its possible combination to increase the water savings and quality of the energy generated in the autonomous micro-hydropower plants. The topic is characterized in the Cuban context and the combined flow-dump load control scheme is presented.

Introduction

Hydropower plants are generally classified as storage hydropower and run-of-river hydropower, the latter also known as a water edge in the Cuban context. These plants play a vital role in the rural electrification of developing countries as a decentralized generation of energy and, in general, they operate autonomously: isolated from the grid and as a single energy source (Ashfaq, Saood, and Singh, 2015; Peña Pupo and Fariñas Wong, 2020). From an economic point of view, the costs of technical and technological solutions to work according to international energy quality standards are contrasted with the high social benefit of these plants; mainly due to the strong economy of scale that characterizes isolated hydropower power plants (IRENA 2019a; Ogayar and Vidal 2009). This problem is amplified taking into account that, in general, mini and micro hydropower plants are used in rural communities whose inhabitants tend to be low-income (Milanés Batista et al., 2020). In surveys carried out during measurement and maintenance works on the autonomous micro-hydropower plants, it has been proven that users disconnect their home electric equipment's when proven experience tells them that power quality is low. This behaviour, from the technical point of view, does not encourage energy consumption, which causes a low use of the available energy carrier (water). This shows a direct relationship between energy quality and energy use.

Cuba has 144 hydropower plants in operation, 107 of which are located in mountainous regions, isolated from the National Electric System (SEN) (Hidroenergía, 2019; Ministerio de Energía y Minas (MINEM), 2020). The above allows the supply of energy to thousands of people, in addition to social and economic objectives. Of the total of the 107 mini and micro-hydropower plants in

Cuba, only six have some mechanism for automatic frequency control, which implies a very low quality of energy, according to legal and techniques Cuban norms (Ministerio de la Industria Eléctrica, 1975; Oficina Nacional de Normalización, 1981) as a consequence do not encourage energy consumption. The frequency regulation mechanism of these six exchanges is achieved by dump load. The dump load control, despite being the most used in isolated power plants, has the disadvantage of being inefficient in terms of the use of the energy carrier when dissipating electrical energy in the form of heat.

Turbine flow regulation uses the energy resource (water) more efficiently; although the temporal response is slower, in addition, its design requires a greater degree of precision when considering the hydraulic transients and their negative effects as the known water hammer (Iliev, Popovski, and Markov, 2012; Souza, Z. d., Moreira, S. A. H., & da Costa, 2018). The combination of the advantages of these two methods could be a way to achieve successful technical performance indexes, with low costs and high-energy efficiency.

To keep hydropower plants operating at their nominal values, several approaches are reported in the specialized literature, some of which consider the use of mechanical energy storage systems through flywheels (Khodadoost Arani et al., 2017), interconnected systems (Datta et al., 2015; Dreidy, Mokhlis, and Mekhilef, 2017) use of micro-grids (Mohanrajan, Vijayakumari, and Kottayil, 2018; Sebastian and Quesada, 2016) and storage of electrical energy (Sebastian and Quesada, 2016; Yuniahastuti, Anshori, and Robandi, 2017). Other methods consider the use of asynchronous generators (Guo, B., Bacha, S., Alamir, M., & Imanein, 2017) and isolated micro-grids (Ali et al., 2018). Some of these solutions do not contemplate autonomous systems, so they are not taken into consideration in the scheme proposed in this work. In the most general case, the alternating current micro-grid integrates the energy supply from several sources, in which the equality of frequencies, voltages, and phases is mandatory for synchronization.

From the point of view of the operation of autonomous mini and micro-hydroelectric power plants, two ways of regulating the generated electric frequency are known: manipulating the flow of water entering the turbine or adjusting the generator load (Kundur, 1994). The first method seeks to adjust the turbine operating point, regulating the inlet water flow. Ninety per cent of Cuba's mini and micro-hydropower plants operate with Pelton turbines of TP-15 and TP-16 models. These have limited frequency regulation capabilities, due to the high costs of commercial speed regulators and the effects of water inertia. This is due to the high head hydraulic circuit, as well as the large value of the opening time of the injectors used to avoid problems of transient pressure in the gate (Iliev et al., 2012; Souza, Z. d., Moreira, S. A. H., & da Costa, 2018).

The second method, based on the use of a dump load, ensures that the turbine works at a fixed operating point: the maximum power, balancing the load that represents the demand of the users with a second resistive load (dump load) connected in parallel (Kundur, 1994). This method of regulation has a simpler design and good performance against impulse and sustained disturbances; however, in classic designs, the nominal power of the dump load is chosen 30% higher than the nominal power (S Doolla and Bhatti, 2006). In this case, it is shown that it is profitable only when hot water is required for different uses (Suryanarayana Doolla and Bhatti, 2006; Vilas Kamble and Akolkar, 2018). Another drawback is related to the presence of harmonics caused by the rectifier switching, which is soluble by applying filters and switching techniques (Bory, P. H., Martínez, G. H., Vázquez, S. L., Chang, M. F., & Enríquez, 2018; Bory Prevez, Martínez García, and Vázquez Seisdedos, 2018). Some research suggests matching the secondary power to the nominal power of the plant, but at a high cost (Yadav and Mathew, 2016). Other authors like Suryanarayana Doolla and Bhatti (2006) propose the reduction of the dump load to 50% of the nominal power through the adjustment of the turbine flow in fixed amounts of 30% and 50%. In previous investigations (Peña et al., 2005; Salhi et al., 2010) a dump load regulator was designed with a dump load nominal value of 30%, obtaining good performance only against small-amplitude sustained disturbances loads.

By means of a mixed electronic regulator in a reduction of the secondary load to 10% of the nominal power is proposed (Kurtz, 2007). In this, according to the authors themselves, empirical rules are used, a load behaviour study is not carried out, and they did not evaluate the most frequent types of disturbances. On the other hand, in Doolla and Bhatti (2006a); (2006b) a mixed regulation scheme is proposed for flow control by means of on-off valves that instantly increase or decrease the turbine inlet flow by default values of 30 % or 50 %. In these works, the electric frequency is maintained according to the designed ones for sustained disturbances of 2,4 % of the nominal power. However, 30-50% flow variation could originate in the penstock of the water hammer well-known physical phenomenon.

In Fong Barrios et al. (2018), a mixed load-flow regulator is proposed, combining a PI regulator for the load and a fuzzy to regulate the flow, refeeding the frequency measurement. This firmware and hardware based on a microcontroller are designed, but it is not intended to minimize the dump load. It also does not refer to compliance with the regulations regarding the permitted frequency variations and the design of the regulators and does not describe how it performs the change of the operating point when the load disturbances exceed the maximum power installed in dump load. These elements indicate that the design of (Fong Barrios et al., 2018) is not oriented to the efficient use of the primary energy resource. In Fong Barrios et al. (2018) and Singh and Singal (2017) a review of the last 20 articles published in the area of load frequency control is presented and refers to the need to take advantage of the energy consumed in the dump load differently, which in the authors' opinion could be a throw of some kind of energy storage or lighting.

The authors of this work consider that the combination of the two methods is an intuitive way to use the energy carrier more efficiently and guarantee the required quality of energy. In this form of operation, it is necessary to adjust the turbine's operating point, so that demand fluctuations are compensated thanks to the speed of dump load control, and immediately through flow control, adjust the operating point of the turbine to the demanded power value. With this new method, one could operate close to demand instead of operating at maximum power. As a result, energy would be supplied according to quality standards and the energy carrier would be used more efficiently by reducing the power of the secondary load considerably. The secondary load value would be based on the desired quality requirements of the electric power, and not based on the nominal power installed, which would bring economic benefits by lowering equipment costs and increasing the efficient use of the energy carrier.

Research problem

The low quality of the electricity and inefficient use of the primary energy carrier in the autonomous micro-hydropower plants cause lower energy consumption, it does not allow the human and economic developments of the inhabitants in the communities isolated from the national electric system.

Research purpose

The objective of this research is to propose a way to make more efficient use of the energy carrier that ensures the electricity produced in the autonomous power plants. This new method meets the required quality standards through the combination of flow control with dump load control.

Novelty

In the scientific literature related is not reported until this moment, the obtaining of the procedure that is based in the combination of the turbine linear flow control method with control of minimal dump load for the frequency control of the autonomous micro-hydropower plants.
The authors proposed the combined control scheme shown in Figure 1, but many research topics are involved like the design of new combined control algorithms, substitution of resistive dump load by useful ones, or new control methods for dump load control.

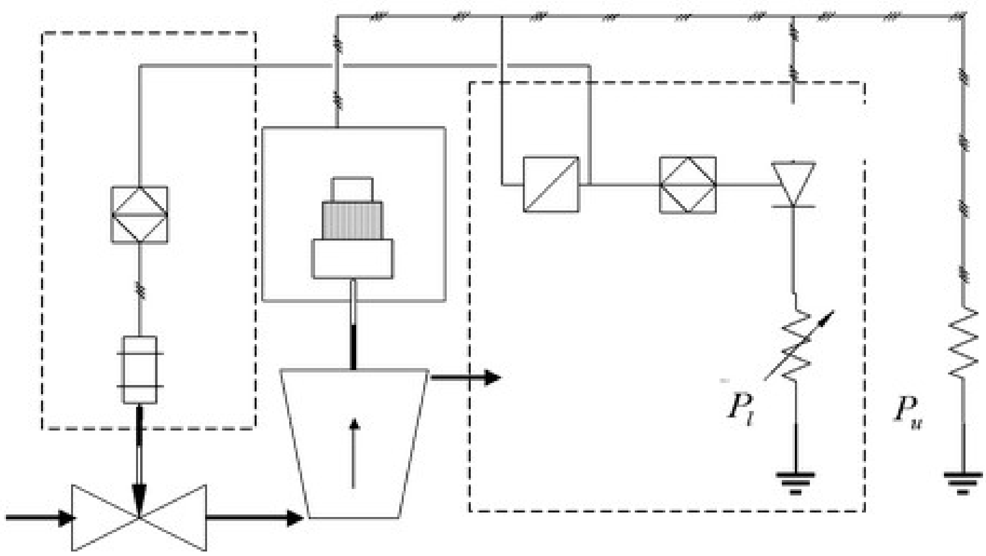

***Figure 1**. The combined frequency control scheme of autonomous micro-hydropower plants. a)Turbine flow control, b) Dump load control.* (Peña Pupo and Fariñas Wong, 2020).

Importance: social, economic and environmental

Hydropower is a renewable energy source based on the natural water cycle. Is the most mature, reliable and cost-effective renewable power generation technology available (IRENA, 2012). Hydropower is the most flexible source of power generation available and is capable of responding to demand fluctuations in minutes. Because of this flexibility, isolated micro-hydropower is an ideal complement to variable renewables as a base energy source in micro-grid integration power sources.

Micro-hydropower can be a cost-competitive option for rural electrification for remote communities in developed and developing countries like Cuba and can displace a significant proportion of diesel-fired generation. In Cuba, another advantage of micro-hydropower technology is that it can have important multiplier effects by providing both energy and water supply services (human supply and irrigation), thus bringing social and economic benefits. That is why water savings, like the authors' procedure propose, have a direct social and economic positive impact. More than 130 million people around the world use autonomous micro-hydropower as an energy source (IRENA 2019a), and more than half of the isolated generation systems is hydropower (IRENA, 2019b) (Figure 2).

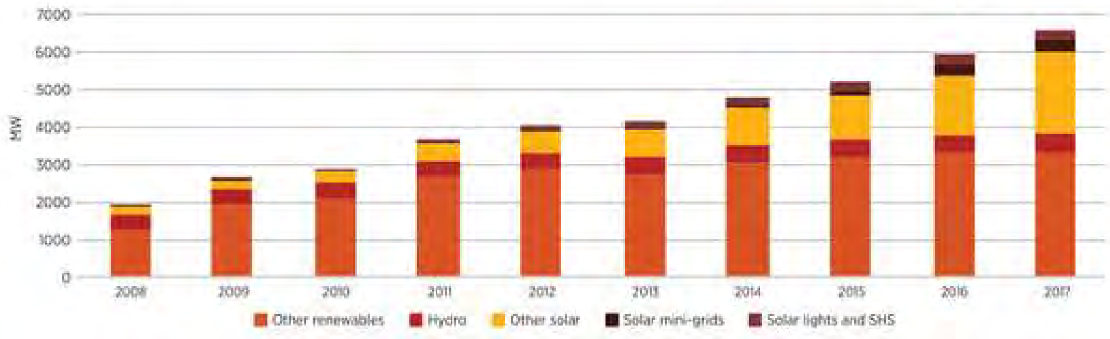

Figure 2. *The capacity of, off-grid renewable energy* solutions (IRENAb, 2019a).

Micro-hydropower is generally CO_2 free in operation, but there are GHG emissions from the construction of hydropower. Run-of-river have a lower environmental impact because they do not change the river flow regimes, either water quality or changes in biodiversity that originate population displacement. In the past, this is an area where hydropower has had a poor track record in some cases.

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V. Conclusions

Concluding remarks

Jyrki Luukkanen

The main research questions this book wanted to respond to were related to the development of the Cuban energy system, its transition and the integration of renewable energy sources in the system.

The understanding of the energy system development requires knowledge of the past and present situation. The management and governance of the energy system during the transition towards a new structure requires a special understanding of the management and governance systems under the new constitution and allocation of planning responsibilities to the local level. The new planning methods are directly related also to changes in the technological system. The change to more distributed electricity production with a larger share of wind and solar production requires new development practices and methods related to different levels of technological development from the local level grid expansion to control of national-level electricity system.

The electricity grid development has to build on the existing grid and the required that the new production modes will entail. The integration of variable renewable energy resources in the grid requires special efforts for maintaining the balance of supply and demand. The variations on the consumption side make the balancing more cumbersome since the peak demand is located at the time when the solar PV production is reduced in the evening. The operation and control of the power system calls for the addition of energy storages in the system to balance the grid.

Cuba has vast resources of renewable energy, especially wind and solar resources. The development of both the wind and solar energy is also related to grid development since the best locations for wind production are in the eastern part of the country while the largest consumption takes place in the Havana area, in the western part. The increase of the transmission capacity will be needed in the transition towards renewables even though the increase of the distributed production of solar energy can provide relief to the transmission needs. The temporal changes in solar production can, however, cause new problems in this sense.

The role of biomass energy is also central in the new developments towards a larger share of renewable energy in the energy mix. The biomass resource utilization has so far mainly concentrated on the use of bagasse in sugar production. The plans for increasing biomass-based production requires the use of wood-based power production. Also municipal waste can provide some possibilities for power production.

The role of hydropower is considerably small in the Cuban power supply because the small rivers of Cuba do not offer possibilities for large hydro projects. However, the role of hydropower can be very important in the future power system by providing opportunities for energy storage using pumped hydro production for balancing supply and demand. The use of battery storages in the grid balancing depends on their future prices. Battery storage will probably function as fast reserves for frequency control but their role as larger energy storages requires a fast decrease of their prices.

The research work carried out by the PhD researchers illustrates the high level of expertise in Cuban universities. The large variety of research topics and the professional handling of complex topics create confidence in the future development possibilities of the Cuban energy system. International cooperation enhances possibilities for the exchange of the latest information and experiences of the trends and future dimensions of the energy system research.

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