Power Generation Planning of Galapagos' Microgrid Considering Electric Vehicles and Induction Stoves

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***Abstract*—Islands located far away from the mainland and remote communities depend on isolated microgrids based on diesel fuel, which results in significant environmental and cost issues. This is currently being addressed by integrating renewable energy sources (RESs). Thus, this paper discusses the generation planning problem in diesel-based island microgrids with RES, considering the electrification of transportation and cooking to reduce their environmental impact, and applied to the communities of Santa Cruz and Baltra in the Galapagos Islands in Ecuador. A baseline model is developed in HOMER for the existing system with diesel generation and RES, while the demand of electric vehicles and induction stoves is calculated from vehicle driving data and cooking habits in the islands, respectively. The integration of these new loads into the island microgrid is studied to determine its costs and environmental impacts, based on diesel cost sensitivity studies to account for its uncertainty. The results demonstrate the economic and environmental benefits of investing in RES for Galapagos' microgrid, to electrify the local transportation and cooking system.**

***Index Terms*—Electric vehicle, induction stove, island communities, microgrid, power generation planning, renewable generation.**

NOMENCLATURE

Indices

e	EV type: 1 for motorcycles, 2 for buses, 3 for cars
g	Diesel Generator index
i	IS user index
j	EV user index
m	meal index: 1 for breakfast, 2 for lunch, 3 for dinner
t	Time index
y	year

Parameters

α_{CO_2}	Emission factor for CO_2 emissions [Ton/kWh]
Δt	Time interval [1 h]
δ_m^{IS}	Time horizon for the start cooking time for each meal m
δ_e	Time horizon for the charging starting time for each EV type e
$\overline{P_e^{EV}}$	Maximum charging power in slow mode for each EV type e [kW]
BC_e	EV battery capacity for each type e [kWh]
CRF	Capital Recovery Factor
CT	Annualized net present total cost for the planning horizon [\$/yr]
D	Number of years for planing horizon
ER_e	Average energy required from a user for each EV type e [kWh]
$ER_{i,m}$	Energy required for each i user for each meal m [kWh]
ET	Total electrical energy served [kWh/yr]
ET_g	Total electrical energy served by generator g [kWh/yr]
N_e^{EV}	Number of EVs from each type e
N_G	Number of Diesel Generators
N_{IS}	Number of ISs
r	Discount rate [%])
$st_{e,j}$	Starting time of charge of each j EV of type e
$st_{i,m}$	Starting time of cooking for each i IS user for meal m

Sets

$\tau_{e,j}$	Time horizon for the charging of each j EV of type e

Variables

Δ_{CO_2}	Carbon dioxyde emissions Difference [%]
Δ_{COE}	Levelized Cost of Energy Difference [%]
Δ_{NPC}	Net Present Cost Difference [%]
CO_2	Carbon dioxyde emissions [Ton/yr]
COE	Levelized Cost of Energy [\$/kWh]
NPC	Net Present Cost [\$]
P_t^{EV}	Total EV load at time t [kW]
P_t^{IS}	Total IS load at time t [kW]
$P_{e,j,t}$	Charging power of each j EV of type e at time t [kW]
$P_{i,t}$	Load of each i IS user at time t [kW]

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I. INTRODUCTION

Isolated microgrids, such as those in islands and remote communities, regularly face a variety of issues due to their geographical isolation. Some of these issues include limited installed capacity, aging generators, energy supply limitations, high fuel costs, high greenhouse gas emissions, and fuel logistics [1]. Over the past decades, Renewable Energy Sources (RESs) have been used to address some of these problems.

Thus, in recent years, some researchers have studied the optimal control and operation of microgrids with RES. For example, in [2], the energy management and operation of a microgrid is analyzed from the perspective of integrating PV generators and distributed energy resources. The authors in [3] study the operation of microgrids with EVs for balancing wind power and load fluctuations. In [4], an optimal interconnection operation of microgrids is presented, considering economics, reliability, and generation issues.

Some other works have examined investments in the context of microgrid planning. Thus, the authors of [5] study the expansion planning for the integration of electricity markets with uncertainty in microgrids, based on a two-stage mixed-integer stochastic optimization problem. In [6], a co-optimization scheme for distributed energy resource planning in microgrids is presented, which shows similar results than HOMER Pro; sizing is determined by using Lagrange multipliers and discrete-time Fourier transforms, and the optimization problem is solved by particle swarm optimization. A chance constrained information gap decision model to manage uncertainties in multi-period microgrid planning is proposed in [7], using a bilinear Benders decomposition method. In [8], the stochastic planning of battery storage systems for isolated microgrids is discussed, based on a stochastic mixed integer non-linear problem model. In [9], an efficient planning algorithm for hybrid remote microgrids is discussed, using a heuristic optimization algorithm. However, [8] considers in their planning model only battery storage systems and [9] only PV systems. Microgrid planning with reconfigurable topologies to address data uncertainties is presented in [10], based on a robust optimization approach. Most of these works have focused on presenting mathematical techniques to solve various planning problems; however, these papers and others do not addressed optimal planning with combined generation and energy storage selection and sizing for long-term planning of microgrids. Furthermore, these works discuss theoretical rather than practical case studies, using limited and assumed data, rather than actual and complete data sets as in the case of this paper.

Although various mathematical models have been proposed for microgrid planning, HOMER Pro remains a widely and reliable tool for microgrid planning purposes, due to its adequate mathematical models and optimization solvers [11]. For example, the authors of [12] use HOMER for an economic evaluation of the integration of a biomass gasification plant in a microgrid, coordinated with demand response resources. In [13], the integration of RES planning in northern remote communities in Canada is discussed based on HOMER. This work is complemented in [14] by presenting a framework and models validated with HOMER for long-term planning of RES integration in remote microgrids.

Just a few works have investigated the addition of new loads in the planning problem, such as electric vehicles (EVs) in microgrids. For example, in [15], the planning problem includes the design of an EV charging station in a case of isolated microgrid based on some assumed data. To the knowledge of the authors, the integration of EVs and ISs in the long-term power generation planning of real microgrids has not yet been studied; this is the main purpose of this paper.

Galapagos is a protected volcanic archipelago of Ecuador where humans living or visiting the islands are negatively impacting its pristine environment, because of the limited resources and the fragility of the eco-system. Population and tourism considerable growth has significant increased the demand for services. In particular, the energy demand in different sectors such as the heavily subsidized transportation, electricity, and propane cooking has increased, raising the pollution in the islands. Furthermore, fuel transportation from the continent to the island presents a risk because of possible spills, which have already happened. For these reasons, the Ecuadorean Government has identified the Galapagos Islands as a national priority for conservation and environmental management, developing the Galapagos Zero Fossil Fuels program, which consist of measures and actions to avoid habitat degradation and ecological impact [16], [17]. Thus, the Ecuadorean government invested and installed photovoltaic (PV) plants, wind turbines, and a battery storage systems in Galapagos [18]. Nevertheless, these changes in generation mix are still not enough to fully address the existing environmental problems.

The Ecuadorean government is considering reducing subsidies for gasoline, diesel and propane [17], which distort energy prices [19], thus creating uncertainties in generation planning.

In this context, the government is proposing additional solutions such as the change from propane stoves to induction ones, and the change from Internal Combustion Vehicles (ICVs) to Electric Vehicles (EVs) [20]. All these changes require studies of the optimal generation planning for Galapagos microgrid, considering the introduction of EVs and ISs, which is the focus of this paper. Thus, the main contributions of this work are the following:

- A proper planning model of a real islanded microgrid is developed based on actual data, which includes yearly measured load, accurate wind and solar profiles validated with measurements, and existing generation and energy sources in the microgrid.
- The integration and impact of EVs and ISs on microgrid planning are studied, through adequate modeling of their load patterns, considering the Ecuadorian government actual plans for the future car fleet deployment, with different kinds of electric vehicles such as cars, motorcycles, and buses, as well as the introduction of IS loads. The expected behavior of EV users and IS owners is considered in the modeling of EV and IS loads, using various EV and IS penetration levels to study uncertainties in the adoption of these technologies.
- The optimal investments in RES are determined considering environmental impact and fuel cost uncertainties for a variety of realistic scenarios, considering that some RESs have been already installed, and demonstrating that additional RES can enhance the economic and environmental conditions of this special environment.

The rest of the paper is organized as follows: Section II presents a brief overview of microgrid planning. Section III discusses the HOMER model of the case study, particularly EVs and ISs. Section IV presents the simulation results and analysis of different cases and scenarios. Finally, Section V highlights the main conclusions and contributions of the paper.

II. Background

A microgrid is described as a cluster of loads, distributed generation units, and energy storage systems operated in coordination to reliably supply electricity, either connected to a host power system at the distribution level at a single point of connection or in isolation from the bulk grid [21]. Generally, a microgrid is able to work in grid-connected and stand-alone mode. Off-grid microgrids do not connect to a main grid and have to operate always in stand-alone mode, since these microgrids are built in areas far from transmission infrastructure. Thus, islands are served by isolated microgrids, where the integration of RES presents particular technical issues that are related to equipment and penetration levels. For these microgrids, diesel generators are usually oversized due to the significant difference between average and peak load, so that generators could run at partial load, which results in low efficiency rates [13]; furthermore, voltage and frequency have to be controlled with the help of local microgrid controllers [22]. These issues play a role in the planning studies addressed in this paper, being accounted for the models through diesel generation loading constraints and reserves.

A microgrid planning process follows specific goals and constraints and has to take into considerations some uncertainties [11]. The planning goals typically include minimizing costs and minimizing emissions, considering power quality and reliability. The problem constraints depend on investments and operational considerations. For islanded microgrids, planning is similar to other microgrids, except that a connection to a main grid is not possible. The three main problems that need to be considered in planning are [11]: power generation mix selection and sizing, equipment siting, and generation scheduling.

Different tools exist for planning a microgrid. In this paper, the power generation mix selection and sizing planning is performed by using HOMER Energy Pro 3.11 [23]. The objective used in this software is, for each case or scenario, to minimize the Net Present Cost defined as follows:

$$NPC = \frac{CT}{CRF} \tag{1}$$

where the capital recovery factor (CRF) is the ratio of an annuity and is defined as follows:

$$CRF = \frac{r(1+r)^D}{(1+r)^D - 1} \tag{2}$$

where the total annualized cost CT includes the sum of total discounted costs, such as new equipment purchase, operation and maintenance, and fuel consumption for year y. The rest of the variables in these or another equations can be found in the Nomenclature section.

The levelized cost of energy is also used here for cost/benefit analyses, and is defined as follows:

$$COE = \frac{CT}{ET} \tag{3}$$

TABLE I
Existing generation and energy storage costs

Option	Capital Cost	Replacement Cost	O&M Cost
Diesel	$0	882 $/kW	26.3 $/kW/yr
PV	$0	5,648 $/kW	38.6 $/kW/yr
Battery	$0	1,481 $/kWh	9 $/kWh/yr
Wind	$0	9,833 $/kW	81.76 $/kW/yr

where the total costs for the planning horizon D does not consider previous investments, which are treated here as sunk costs. CO_2 emissions are also used here for evaluation purposes and are calculated based on the diesel generator characteristics, as per the following equation:

$$CO_2 = \sum_{g=1}^{N_G} \alpha_g ET_g \tag{4}$$

HOMER allows determining the technical feasibility and life-cycle costs of a microgrid for each hour of the year for power generation planning [23]. It includes its own proprietary robust optimization algorithm for identifying least-cost options, simulating different cases for an entire year, and determining different outputs, such as NPC, COE, and CO_2 emissions, among others. For this purpose, the user has to specify the required equipment models and associated input data, such as microgrid location, demand, generation search space, equipment costs, and operation, and maintenance costs. The considered microgrids include equipment such as solar PV, wind turbines, diesel generators, and others. It is also possible to make sensitivity analyses of variables, which allows to determine their impact on planning outputs. The HOMER model constraints include supply-demand balance and generation adequacy limits; generation limits; new generation capacity; useful-life of generation sources and batteries; operation and maintenance schedules; battery State Of Charge (SOC) and charging/discharging limits; and others. Moreover, HOMER allows the user to define the size or quantities of the different components for the search space, or to use its own search optimization tool, which simulates all possible combinations of the components in the search space; the latter option is used here.

III. Case Study

In this section, the microgrid model for studying the power generation planning problem of the interconnected islands of Santa Cruz and Baltra is presented. The main objective is to minimize the NPC, using the COE and CO_2 emissions reduction for cost benefit analysis. The schematic of the proposed configuration of the scheduled microgrid is represented in Fig. 1. Several sets of input data are required for HOMER modeling, which are detailed next. The cost data of the existing generation and energy storage is summarized in Table I.

A. Electricity Costs

The electricity is distributed by the local distribution company Empresa Eléctrica Provincial Galapagos (Elecgalapagos).

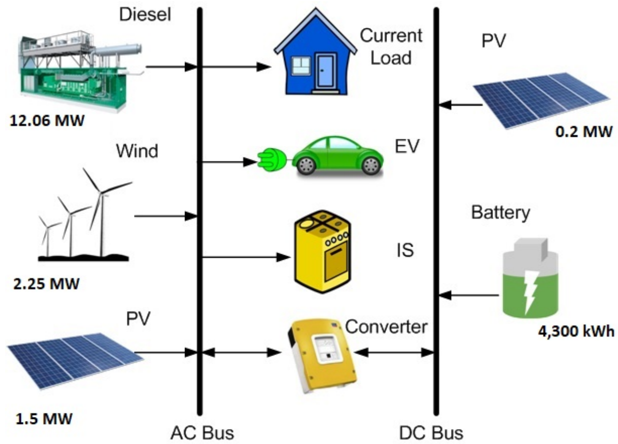

Fig. 1. Considered microgrid configuration.

In Ecuador, the electricity sector is vertically integrated, and thus there is no electricity wholesale market. There is a tariff for each type of customer, which is not linked to the real costs of electricity generation, distribution, and transmission in real time. The electricity cost for all customers in Galapagos has been fixed at 9.1 c$/kWh [24].

B. Residential Load

As part of the supply-demand balance constraint, HOMER allows to define primary and secondary loads. The primary load selected here corresponds to the existing loads, and the secondary load is composed of the new EV and IS loads.

In Fig. 2, the residential load in Santa Cruz is depicted based on [25]. Note in Fig. 2 (a) that the load is at its lowest in September and October, and at its highest in March and April, corresponding to months with low and high presence of tourists, respectively. Furthermore, as shown in Fig. 2 (b), the lowest load in a day is during hour 4 and the highest during hour 18, and in the last months of the year, the load trends are relatively heterogeneous, as seen in Fig. 2 (c).

C. Diesel Generation

The generator model in HOMER requires the following information: capacity, fuel resource, fuel curve, costs, emissions, lifetime, and maintenance schedules. Thus, seven Caterpillar diesel generators are installed with a maximum energy efficiency of 13.77 kWh/gallon, and a total installed capacity of 5.26 MW [26]. There are 4 Hyundai diesel generators that have been installed in recent years, with a total cost of $1,500,000 each including building installation, and an installed capacity of 1.7 MW each, with a maximum efficiency of 15.5 kWh/gallon [26]. Since Hyundai generators are not available in the HOMER library, the corresponding models were built for HOMER based on available manufacturer data sheets. All diesel generators are assumed to have a minimum load ratio of 25% [27].

Due to reliability issues, at least one generator is always running. Since HOMER can give results where only renewable energy is operating, which is technically incorrect, one Hyundai generator was forced to be always running; during its maintenance, the others generators are assumed to be running. The lifetime of diesel generators is commonly 90,000 h, and considering that 2 Hyundai generators were installed in 2015 and 2 others in 2016, it was assumed a remaining life of 75,000 and 80,000 h, respectively, for these generators. The remaining life of the Caterpillar generators was assumed to be 40,000 h due to lack of information, i.e. half life, given their age; however, their influence on the model is very small because of their low efficiency. Valve set and inspection maintenance takes place every 2,500 h, with 24 h of down time, and major maintenance overhaul takes place every 20,000 h, with 72 h of down time [28]. The total operation and maintenance costs for all the diesel generators in 2015 were $195,000 for a total power of 7.41 MW [28]; from these values, the operation and maintenance cost can be estimated to be 26,316 $/MW per year.

In the continent, operating reserves have a minimum value of 5% [29]. Considering that the islanded system is off-grid, these values were assumed here to be 10% of the load for diesel generation, 25% of the solar output, and 50% of the wind output wind based on [30]. Note that operating reserves are selected based on a practical and pessimistic "rule of thumb" typically used in these types of studies, which is considered adequate by utilities.

In Ecuador, the end-user pays only 23% of the overall cost of diesel [31]. Hence, diesel end-user price is 0.27 $/l [32]; however, the real price of diesel in continental Ecuador is 1.17 $/l. Additionally, the fuel transportation cost to the island can be estimated at 0.50 $/l [33]. Therefore, the total real diesel price used here is 1.67 $/l.

D. PV and Battery

The HOMER PV model requires the following information: capacity, solar profile, costs, lifetime, and ac or dc connection. To obtain the required supply profile for the solar PV array in Galapagos, the solar profile of the islands was used.

The PV plant is located near Puerto Ayora, which is the main city in Santa Cruz island. It has 6,006 PV panels of 250 W each, and is connected in ac to Puerto Ayora substation through a 13.8 kV feeder. It has an installed power of 1,500 kWp and it is directly connected to the ac bus. The total installation cost was $10,600,000, which results in 7,067 $/kW. The total operation and maintenance costs including converter is 58,032 $/yr [18]; therefore, the individual operation and maintenance cost of each PV panel used here is 9.66 $/yr. These costs are reasonable, based on the authors work in remote communities in Canada, where small 10-20 kW PV systems installed 5 years ago cost between $8,000 and $10,000/kW. These costs are relatively high because deployment costs of equipment in remote locations is significantly higher than for other systems, due to costly transportation and other logistical and deployment complexities.

There is another PV plant in Baltra Island with dc connection and a converter system of 91 inverters of 17 kW each, with a power capacity of 200 kWp and an energy storage system of 4,300 kWh, with a total cost of $9,390,000 [18];

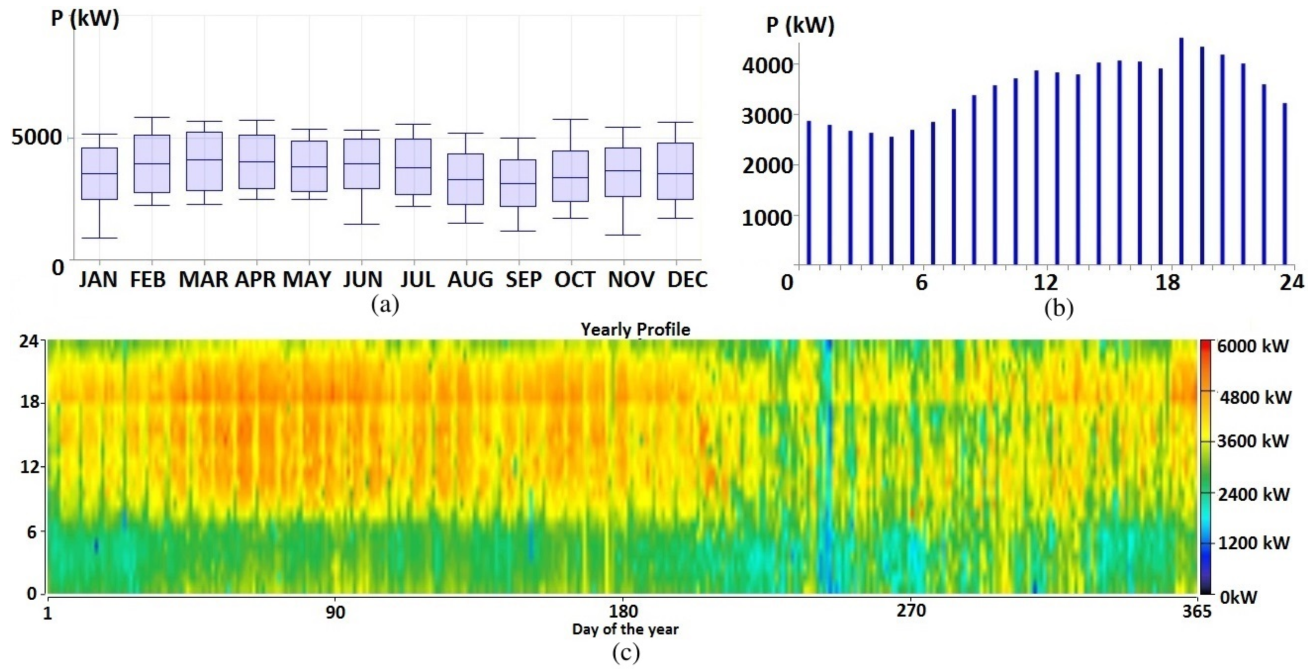

Fig. 2. Existing load in Santa Cruz: (a) Box and Whisker plot of monthly profiles; (b) example of a daily profile; (c) annual load intensity plot

its operation started in February 28^{th} 2016. Considering the 7,067 $/kW for the Santa Cruz PV plant, this yields a PV plant cost of $1,420,000 and a battery system cost of $7,970,000. For replacement, it is considered here that only 80% of the installation costs are required, since studies and some construction costs are not needed; hence, the PV replacement costs can be estimated to be 5,653 $/kW [34], based on the fact that this installation was done in 2014 and on the decreasing costs of solar PV in recent years.

Two hourly solar generation profiles were compared to obtain the most accurate. The first profile was generated through HOMER's solar database, which is linked to NASA's Surface Meteorology and Solar Energy Database, considering the latitude and longitude of Santa Cruz island (00°38'S and 90°21'W); for the PV plant located in Baltra Island, similar profiles were defined. The second profile was obtained based on [25], resulting in very similar input. Hence, the first profile was used here for the model, because there was some missing information in the second one. Fig. 3 illustrates the annual average daily radiation and clearness index used here; note that the solar radiation is high in March and October, while is low in June and July. The annual average solar radiation is 6.0 kWh/m^2/day.

The HOMER battery model required the following information: battery quantities, costs, and lifetime. Hence, the existing battery system consists of 4,000 kWh Lead-Acid and 300 kWh Li-ion batteries; however, HOMER only allows to define one battery system, thus a 4,300 kWh Lead Acid system was used here, with a string size of 39 modules of 12 V adding up to 468V, which corresponds to the grid voltage. Therefore, based on the estimated cost of the battery system, the battery replacement was estimated to be 1,481 $/kWh, with a life of 10 years or 1,100 cycles, as per [16] and [34].

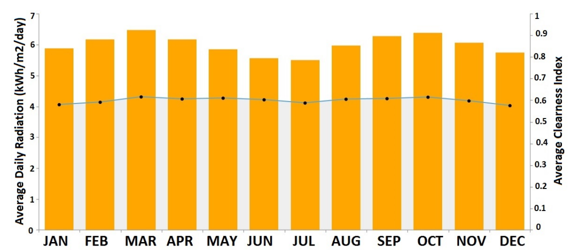

Fig. 3. Annual average daily radiation and clearness index.

E. Wind

The HOMER wind model requires the following information: capacity, wind profile, costs, lifetime, and power curves, so that from the wind profile, the generation curve can be obtained. There are 3 U57 wind generators with a hub height of 68m located in Baltra island, which are connected to the electric grid of Santa Cruz island through a 34.5 kV line. Each wind turbine has an installed capacity of 750 kW, for a total wind capacity of 2.25 MW. The wind turbine power curve was modeled based on the information in [35], due to the absence of this wind turbine model in the HOMER library.

The total deployment cost of the three turbines and its equipment was 27,655,606 $/yr, as per [36], where 80% of this value was used as replacement cost in HOMER, as in the case of PV. The total operation and maintenance costs are 183,968$/yr [28]; therefore, an individual turbine was estimated to have a maintenance cost of $61,323.

Three hourly wind generation profiles were compared to obtain the most accurate. The first profile was generated through HOMER's database, which is based on NASA's Surface Meteorology and Solar Energy Database, the second was obtained based on [25], and the third was obtained from a simulation

Fig. 4. Annual average wind speed.

with VAISALA Energy [37], which allows simulating the wind profiles in the islands. The second profile was not reliable because of significant variations on the obtained wind profiles, with the third being finally selected, since the simulation can be considered more accurate than the first one, as it is based on real measurements as opposed to satellite data. Fig. 4 illustrates the average wind profile, whose range is 3.3 m/s to 5.16 m/s, which is relatively low; note that the average maximum wind speeds appear from July to September, and the lowests can be observed in March. The annual average wind speed is 4.4 m/s.

F. EV Demand

The vehicle fleet in Santa Cruz is composed by 1,326 vehicles [38]. The most important type in the vehicle fleet is motorcycles, because of their cost and their easier transportation to the islands. The government has tried to limit the number of motorcycles, but limited controls in shipments has not allowed to enforce this. Santa Cruz is the island with the largest vehicle fleet in Galapagos with 53% of all vehicles [16].

The present cost of the EVs is much higher than ICVs. However, the Ecuadorean government is taking actions to preserve the eco-system of Galapagos, including incentives to change from ICVs to EVs, to address greenhouse gas and fuel transportation issues [16], [20].

Several works on modeling EV demand profiles have shown that these depend on local conditions. Hence, the EV demand model developed here was based on traffic data information for the Galapagos Islands [39]. Three different types of vehicles were considered: motorcycles, buses, and cars; other types were not included because they are not numerous and hence present low demand. Based on [39], distances and schedules were analyzed in order to obtain the EV characteristics shown in Table II. The charging starting time for each EV $st_{e,j}$ was defined as a random number generated within the given time horizon δ_e in Table II. The time horizon for the charging of each EV was then defined as: $\tau_{e,j}=\left[st_{e,j}, st_{e,j}+\frac{ER_e}{\overline{P_e^{EV}}}\right]$, assuming that all EVs charge at its maximum power $\overline{P_e^{EV}}$, defined in Table II, until its maximum SOC is reached. Therefore, the demand of each EV can be defined as follows:

$$P_{e,j,t} = \begin{cases} \overline{P_e^{EV}} & \text{if } t \in \tau_{e,j} \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

TABLE II
EV CHARACTERISTICS

EV type	Motorcycle	Bus	Cars
$\overline{P_e^{EV}}[kW]$	1	60	7,2
BC_e [kWh]	4	324	28
$ER_e[kWh]$	3	280	24
N_e^{EV}	611	46	467
$\delta_e[h]$	16-20	12-22	05-12 & 22-02

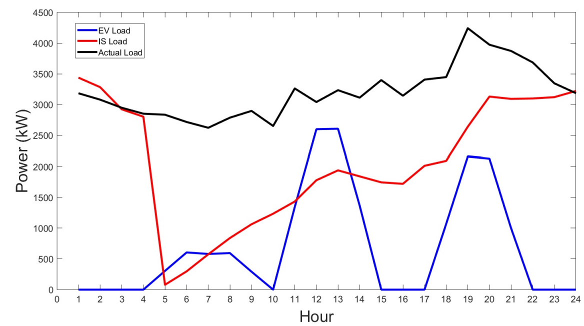

Fig. 5. EV, IS, and other loads for a day.

Hence:

$$P_t^{EV} = \sum_{e=1}^{3} \sum_{j=1}^{N_e^{EV}} P_{e,j,t} \ \forall t \quad (6)$$

Note that the EV load is generated for each day of the year and not replicated by HOMER using a random daily variability.

In Fig. 5, the total EV demand for 100% penetration is illustrated for a day. This demand was modeled in HOMER as a secondary load, including also IS loads, depending on different penetration levels for various scenarios.

G. IS Demand

Induction heating is a technique for applications such as forging, surface hardening, and cooking. It is nowadays a very attractive technology due to its high power density that allows fast heating [40]. The main domestic application of induction heating is ISs, which significantly improves safety, cleanness, and efficiency compared to flame or resistance stoves. An IS is composed of a vitroceramic glass, an inductor, and a power electronics and control system, which includes an electromagnetic compatibility filter, a rectifier and filter, an inverter, and an inductor-pot. The output power is usually up to 4 kW and the switching frequencies range from 20 kHz to 100 kHz [41].

The government of Ecuador currently subsidizes propane or liquefied petroleum gas (LPG). Thus, 15 kg of propane for an end user costs $1.60, which results in a total subsidy for the country of about $690 million per year, including smuggling to neighboring countries of around 20%. About 78% of the domestic propane demand is imported, which negatively affects the trade balance of Ecuador [42]. Additionally, the real cost of the propane is higher in Galapagos, because of transportation from the continent. For these reasons, and considering the environmental impact of this fuel, Ecuador is implementing a

TABLE III
IS CHARACTERISTICS

Meal	Breakfast	Lunch	Dinner
δ_m^{IS} [h]	05-09	11-14	18-21
$ER_{i,m}$ [kWh]	0.3-0.6	1-2	0.8-1.6

National Efficient Cooking Program (PEC in Spanish) based on ISs [43], with the goal of reducing imports of this fuel, while increasing the use of hydroelectrical energy.

In Santa Cruz, there are 15,393 inhabitants and 5,280 families, who could be assumed as the number of residential propane users [16]. Restaurants and hotels were not considered here as part of the IS demand, because owners prefer propane for cooking [44].

The IS demand model used here is based on typical meal preferences, including schedules and types of meals. The starting cooking time $st_{i,m}$ was defined as a random number generated within the given time horizon δ_m^{IS} in Table III, which was estimated according to typical Ecuadorean meal hours based on [39]. In addition, as per [42], the meal types and the associated energy required to cook them were considered to obtain the $ER_{i,m}$ ranges shown in Table III. Considering that the time to cook a meal is typically less than an hour, an average IS power was assumed for each hour and user as follows:

$$P_{i,t} = \begin{cases} \frac{ER_{i,m}}{\Delta t} & \text{if } t = st_{i,m} \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

Thus:

$$P_t^{IS} = \sum_{is=1}^{N_{IS}} P_{i,t} \;\forall t \quad (8)$$

Note that the IS load is also generated for each day of the year and not replicated by HOMER using a random daily variability. In Fig. 5, the total IS demand for 100 % penetration is depicted for a day.

H. Additional Inputs

A discount rate r of 12% was used as proposed in [19], [29], together with an inflation rate of 2%. The assumed planing horizon was 20 years.

IV. Results and Discussion

Nine different scenarios were studied, which combine different penetration levels of EVs (0, 50, and 100%) and ISs (0, 50, and 100%). These different scenarios were considered based on the interest of the Ecuadorean government on introducing EVs and ISs, and to reflect the fact that the exact penetration of these new loads would be uncertain. In Table IV, the average electricity consumption (AEC) of the simulated load and the peak demand (PD) for each scenario are presented. Note that the maximum PD corresponds to Scenario 9, with 10,688 kW, which can be supplied by all available diesel generators.

For all the scenarios, two cases were simulated. The first case considers the existing generation configuration without new investments, and the second considers investment in both more generation capacity and battery storage, including renewables, using HOMER's search space optimization tool. For the latter, a search space was defined for all the scenarios in order to find the optimal generation configuration. In addition, several simulations were performed considering different types of wind turbines to determine which model is the most suitable for the wind profile; the U58 wind turbine was found to be the best. Furthermore, in the search space, only Hyundai generators were considered, since Caterpillar generators are less efficient.

TABLE IV
DEMAND CHARACTERISTICS FOR EACH SCENARIO

	Penetration			
Scenario	IS [%]	EV [%]	AEC [kWh/d]	PD[kW]
1	0	0	88,574	5,863
2	0	50	11,310	7,265
3	0	100	137,388	8,650
4	50	0	96,889	7,040
5	50	50	121,333	8,362
6	50	100	145,753	9,864
7	100	0	105,208	8,309
8	100	50	129,668	9,294
9	100	100	154,041	10,688

TABLE V
NEW INVESTMENT COSTS

Options	Capital Cost	Replacement Cost	O&M Cost
Diesel	882 \$/kW	882 \$/kW	26.3 \$/kW/yr
PV	5,648 \$/kW	5,648 \$/kW	38.6 \$/kW/yr
Battery	1,481 \$/kWh	1,481 \$/kWh	9 \$/kWh/yr
Wind	9,833 \$/kW	9,833 \$/kW	81.76 \$/kW/yr

The new investments costs are presented in Table V. The system configuration of the simulated HOMER model for the search space in Scenario 9 is depicted in Fig. 6. Observe that additional generator, PV, wind turbine and battery are included to search for the optimal new investments. An additional converter has not been added, since it is included in the price of the PVs and battery, and thus it was oversized in the model. The Electric Load #1 corresponds to the actual residential load, and #2 corresponds to the EV and IS loads. Note that the sum of the two peak demands are not equal to the total peak demand, because the latter does not take place at exactly the same time as the two load peaks.

Considering that the diesel price in the 20-year planning horizon is uncertain, a sensitivity analysis for the diesel price was carried out, based on an average increase of diesel price of either 50% or 100% for the considered planning horizon, as per [45]. This results in diesel prices of 2.26 \$/l and 2.84 \$/l, respectively, assuming the same transportation cost of 0.50 \$/l.

A. Costs and Emissions Comparisons

In Table VI, the results for costs and emissions for all the scenarios for the current diesel price of 1.67 \$/l are shown. Observe that the COE, NPC, and CO_2 emissions are lower for all scenarios considering new investments. The optimal

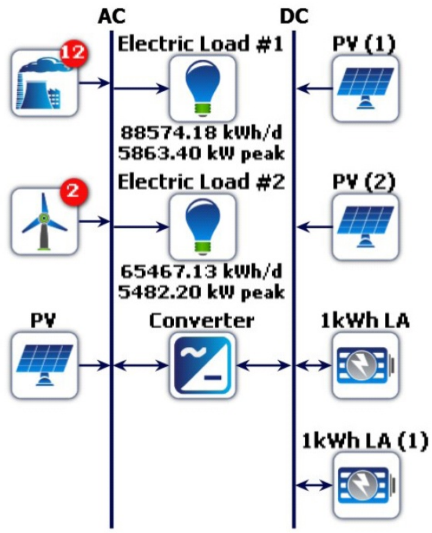

Fig. 6. System configuration of the simulated HOMER model for Scenario 9.

results were obtained for new PV capacity only, since new wind turbines, diesel generators, and battery storage resulted in higher NPCs. It should be noted that replacing 100% of ICVs would reduce emission by at least 30 kTon/yr, and replacing 100% of propane stoves would reduce emissions by least 5 kTon/yr.

To compare the cases with and without new generation investments, the percentage changes in NPC, COE, and CO_2 were calculated, as in [46]:

$$\Delta_{NPC} = \frac{NPC_{inv} - NPC_0}{NPC_{inv}} \tag{9}$$

$$\Delta_{COE} = \frac{COE_{inv} - COE_0}{COE_{inv}} \tag{10}$$

$$\Delta_{CO_2} = \frac{CO2_{inv} - CO2_0}{CO2_{inv}} \tag{11}$$

Thus, Figs. 7, 8, and 9 depict respectively the NPC, COE, and CO_2 differences for all scenarios and various diesel prices. Note that all the changes are negative, which shows that with PV investments, all NPC, COE and CO_2 emissions decrease. Observe also that an increase of diesel price leads to a decrease of Δ_{NPC}, Δ_{COE}, and Δ_{CO_2}, for all scenarios, which means that if diesel price is higher, it is better to invest in new PV generation. For the highest average value of 2.84 $/l for diesel, the NPC and COE differences are significant, with reductions of more than 12% for NPC in Scenario 8, and more than 10% of COE for most scenarios. With higher diesel costs, the replacement costs decrease (due to higer use of RES instead of diesel generators), but the operating and especially the investments costs increase. Note that the CO_2 reductions are significant for all scenarios and diesel prices, which would be desirable for the environment of the islands.

B. Energy Supplied

In Fig. 10, the amount of energy supplied for all the scenarios, with and without investments and various diesel

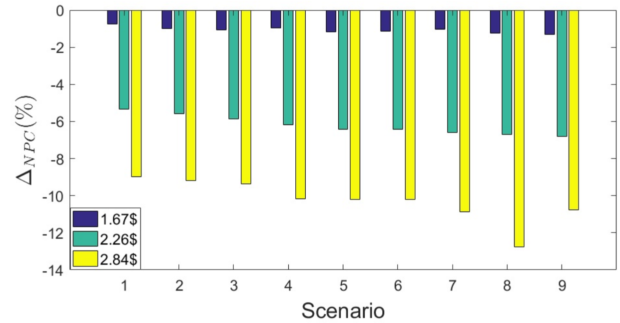

Fig. 7. NPC differences with and without PV investments for different scenarios and diesel prices.

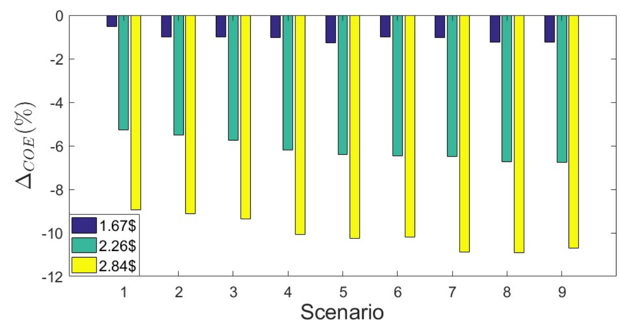

Fig. 8. COE differences with and without PV investments for different scenarios and diesel prices.

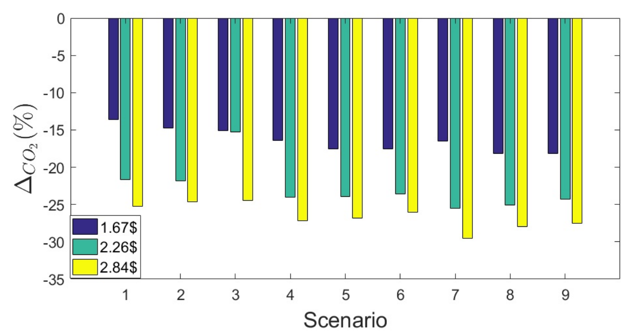

Fig. 9. CO_2 differences with and without PV investments for different scenarios and diesel prices.

prices, is illustrated. Note that without PV investments, the RES energy supplied does not change between each scenario, with only diesel energy increasing, and with PV investments, the RES energy supplied increases, especially as diesel prices increase. Observe also that an increase of diesel price leads to an small increase of RES energy supplied, for all scenarios.

C. Daily Operation

Fig. 11 depicts the daily profiles of the load, the diesel generation, and RES for Scenario 1, with and without PV investments, for a typical week. Observe a significant increase in RES power and a decrease in diesel around noon each day in the case of new investments.

In Fig. 12, the daily profiles of the load, diesel generation, and RES for Scenario 9, with and without PV investments, for a typical week are illustrated. Note that in this case,

TABLE VI
SYSTEM COSTS AND EMISSIONS AT 1.67 $/L DIESEL

Scenario	Penetration		COE [$/kWh]		NPC [M$]		CO_2 [kTon/yr]		New PV [MW]		New Capital [M$]	
	IS [%]	EV [%]	New Invest.		New Invest.		New Invest.		New Invest.		New Invest.	
			No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
1	0	0	0.383	0.381	106.97	106.17	18.43	15.92	0	2.28	0	12.9
2	0	50	0.395	0.391	140.43	139.03	24.45	20.84	0	3.24	0	18.3
3	0	100	0.402	0.398	173.93	172.09	30.47	25.88	0	4.12	0	23.2
4	50	0	0.388	0.384	118.33	117.17	20.48	17.12	0	3.03	0	17.1
5	50	50	0.398	0.393	151.91	150.15	26.51	21.87	0	4.17	0	23.6
6	50	100	0.404	0.400	185.66	183.55	32.59	26.88	0	5.12	0	28.9
7	100	0	0.392	0.388	129.74	128.41	22.54	18.33	0	3.33	0	18.8
8	100	50	0.401	0.396	163.60	161.58	28.62	23.42	0	4.66	0	26.3
9	100	100	0.407	0.402	197.70	195.84	34.75	28.45	0	5.62	0	31.7

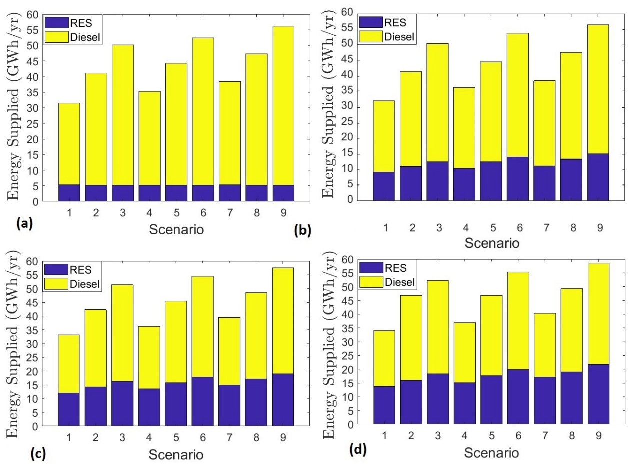

Fig. 10. Energy supplied by source (a) without investments and 1.67 $/l diesel); (b) with investments and $1.67 $/l diesel); (c) with investments and $2.26 $/l diesel; and (d) with investments and 2.84 $/l diesel.

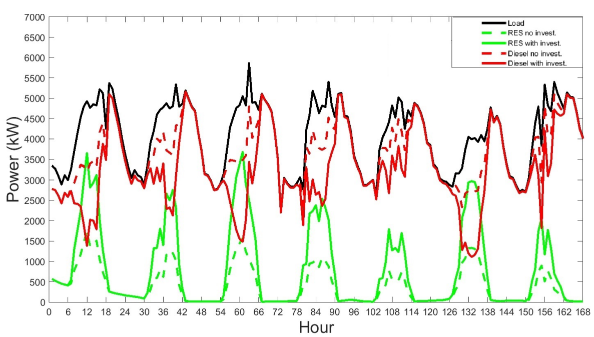

Fig. 11. Scenario 1 load and generation profiles for a typical week.

which presents the highest EV and IS loads, the RES peak is considerably higher with new PV investments compared to Scenario 1, which has no EV or IS loads. Moreover, in Scenario 9, observe that the load presents peaks at noon, due especially to IS use, which coincide with the PV peak; this confirm the selection of PV as the most suitable new generation investment. It should be highlighted that, due to high replacement costs, batteries are seldom dispatched.

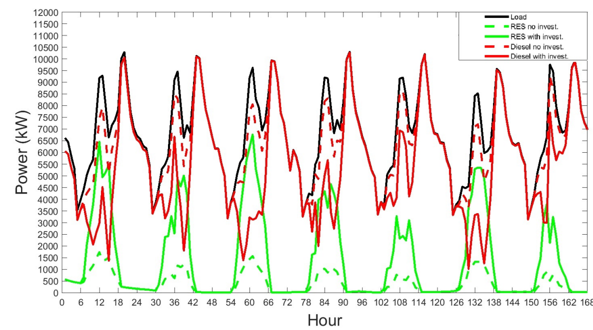

Fig. 12. Scenario 9 load and generation profiles for a typical week.

D. Model Accuracy and Uncertainties

Since existing input data from load, PV and wind generation, and actual model data for PV, batteries, diesel generators and wind turbines was used in HOMER, one can assume adequate results for the model, especially if uncertainty is considered for the more volatile data, i.e., diesel fuel costs and EV and IS load penetration. Thus, the load forecast is a major source of uncertainty; fixed loads can be generally forecasted with high accuracy, which is not the case for flexible loads such as EVs and ISs [47]. In the present model, the fixed load represents existing residential load, obtained from actual data. Some additional simulations were performed considering an increase in the residential load through the planning years, considering a population increase in Santa Cruz of 1.8 % per year [48]. However, the variations of the COE, NPC, CO_2, and new PV investments were less than 1%, compared to the cases without yearly increases in residential load; therefore, load increase was not considered in the studies presented here.

Flexible load is represented by the new IS and EV loads, which can significantly vary in the coming years. Hence, nine scenarios were studied, to analyze the impact of uncertainties in these loads on the power generation planning problem.

Another source of uncertainty is the variable RES generation, since it is not easy to forecast for the daily operation of microgrids [47], which was considered in the model through proper generation reserves. Since the model considered actual and accurate RES generation data, their uncertainty can be assumed to be properly captured in the studied planning model.

V. Conclusions

In this paper, an optimal power generation planning study has been presented for the microgrid of Santa Cruz and Baltra in the Galapagos Islands, to assess the impact of new EV and IS loads. This planning model was built in HOMER Energy, where nine scenarios were simulated to determine the impact of different penetration levels of EVs and ISs, with and without new generation and energy storage investments. To consider diesel price uncertain, a sensitivity analysis based on three different projected diesel prices was performed.

The obtained results demonstrate that investing in new PV generation would improve system costs, especially if diesel prices are high. Moreover, it is shown that investing in PV would reduce considerably diesel consumption, thus CO_2 emissions, which would be environmentally beneficial for the protected islands. Note that the change to EVs and ISs would require significant c ommitment f rom t he Ecuadorean government and users to adopt them, but it would mitigate transportation and cooking economic and environmental issues.

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References

[1] M. Arriaga, C. A. Canizares, and M. Kazerani, “Northern lights: Access to electricity in Canada’s northern and remote communities,” *IEEE Power Energy Mag.*, vol. 12, no. 4, pp. 50–59, 2014.

[2] H. Kanchev, D. Lu, F. Colas, V. Lazarov, and B. Francois, “Energy management and operational planning of a microgrid with a PV based active generator for smart grid applications,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4583–4592, 2011.

[3] H. Yang, H. Pan, F. Luo, J. Qiu, Y. Deng, M. Lai, and Z. Y. Dong, “Operational Planning of Electric Vehicles for Balancing Wind Power and Load Fluctuations in a Microgrid,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 592–604, 2017.

[4] L. Che, X. Zhang, M. Shahidehpour, A. S. Alabdulwahab, A. Abusorrah, “Optimal Interconnection Planning of Community Microgrids With Renewable Energy Sources Optimal Interconnection Planning of Community Microgrids With Renewable Energy Sources,” *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1054–1063, 2017.

[5] A. Khayatian, M. Barati, and G. Lim, “Integrated Microgrid Expansion Planning in Electricity Market with Uncertainty,” *IEEE Trans. Power Syst.*, vol. PP, pp. 1–9, 2017.

[6] C. Yuan, M. Illindala, and A. Khalsa, “Co-Optimization Scheme for Distributed Energy Resource Planning in Community Microgrids,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 4, pp. 1–1, 2017.

[7] X. Cao, J. Wang, and B. Zeng, “A Chance Constrained Information-Gap Decision Model for Multi-Period Microgrid Planning,” *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2684–2695, 2018.

[8] H. Alharbi and K. Bhattacharya, “Stochastic Optimal Planning of Battery Energy Storage Systems for Isolated Microgrids,” *IEEE Trans. Sustain. Energy*, vol. PP, pp. 1–16, 2017.

[9] S. Mohamed, M. Ismail, M. F. Shaaban, E. Serpedin, and K. Qaraqe, “An Efficient Planning Algorithm for Hybrid Remote Microgrids,” *IEEE Trans. Sustain. Energy*, vol. PP, pp. 1–10, 2018.

[10] F. S. Gazijahani and J. Salehi, “Robust Design of Microgrids with Reconfigurable Topology under Severe Uncertainty,” *IEEE Trans. Sustain. Energy*, vol. 9, no. 2, pp. 559–569, 2018.

[11] C. Gamarra and J. M. Guerrero, “Computational optimization techniques applied to microgrids planning: A review,” *Renew. Sustain. Energy Rev.*, vol. 48, pp. 413–424, 2015.

[12] L. Montuori, M. Alcázar-Ortega, C. Álvarez-Bel, and A. Domijan, “Integration of renewable energy in microgrids coordinated with demand response resources: Economic evaluation of a biomass gasification plant by Homer Simulator,” *Appl. Energy*, vol. 132, pp. 15–22, 2014.

[13] M. Arriaga, C. A. Cañizares, and M. Kazerani, “Renewable Energy Alternatives for Remote Communities in Northern Ontario, Canada,” *IEEE Trans. Sustain. Energy*, vol. 4, no. 3, pp. 661–670, 2012.

[14] M. Arriaga, C. A. Cañizares, and M. Kazerani, “Long-Term Renewable Energy Planning Model for Remote Communities,” *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 221–231, 2016.

[15] O. Hafez and K. Bhattacharya, “Optimal design of electric vehicle charging stations considering various energy resources,” *Renew. Energy*, vol. 107, pp. 576–589, 2017.

[16] “Plan Galapagos,” Consejo de Gobierno del Regimen Especial de Galapagos, Tech. Rep. [Online]. Available: http://extwprlegs1.fao.org/docs/pdf/ecu166016.pdf

[17] M. Ponce-Jara, M. Castro, M. Pelaez-Samaniego, J. Espinoza-Abad, and E. Ruiz, “Electricity sector in Ecuador: An overview of the 2007–2017 decade,” *Energy Policy*, vol. 113, no. August 2017, pp. 513–522, 2018.

[18] “Proyectos,” Elecgalapagos, Tech. Rep. [Online]. Available: http://www.elecgalapagos.com.ec/proyectos

[19] “Aspectos de sustentabilidad y sostenibilidad social y ambiental,” ARCONEL and MEER, *Plan Maestro de Electrificación 2013-2022*, vol. 53, no. 9, pp. 1689–1699, 2013. [Online]. Available: http://www.regulacionelectrica.gob.ec/wp-content/uploads/downloads/2015/12/Vol4-Aspectos-de-sustentabilidad-y-sostenibilidad-social-y-ambiental.pdf

[20] “Resumen Ejecutivo de Rendicion de Cuentas 2016,” Elecgalapagos, Tech. Rep., 2016. [Online]. Available: http://www.elecgalapagos.com.ec/transparencia/files/RENDICION%20DE%20CUENTAS%20PERIODO%202016/Informe%5F2016%5FELECGALAPAGOS.pdf

[21] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Cañizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. A. Jiménez-Estévez, and N. D. Hatziargyriou, “Trends in microgrid control,” *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, 2014.

[22] B. J. Brearley and R. R. Prabu, “A review on issues and approaches for microgrid protection,” *Renew. Sustain. Energy Rev.*, vol. 67, pp. 988–997, 2017.

[23] “HOMER Software,” HOMER Energy, 2018. [Online]. Available: http://www.homerenergy.com/

[24] “Pliego tarifario para las empresas eléctricas,” ARCONEL, Tech. Rep., 2016. [Online]. Available: http://www.regulacionelectrica.gob.ec/wp-content/uploads/downloads/2018/01/2018-01-11-Pliego-y-Cargos-Tarifarios-del-SPEE-20182.pdf

[25] J.-M. Clairand, J. Rodríguez-García, P. Pesántez-Sarmiento, and C. Alvarez-Bel, “A Tariff System for Electric Vehicle Smart Charging to Increase Renewable Energy Sources use,” in *2017 Proc. IEEE PES Innov. Smart Grid Technol. Conf. Latin America (ISGT Latin America)*, 2017, pp. 0–5.

[26] C. Paz and D. Anazco, “Iluminando al Patrimonio Natural de la Humanidad,” Elecgalapagos, Tech. Rep., 2015. [Online]. Available: http://www.elecgalapagos.com.ec/pdf2015/M09/Revista%20institucional.pdf

[27] L. C. Vintimilla, “Proyecto Eólico San Cristóbal Galápagos - Ecuador,” Elecgalapagos, Tech. Rep. [Online]. Available: http://www.iner.gob.ec/wp-content/uploads/downloads/2013/05/11-Luis-Vintimilla-EOLICSA1.pdf

[28] “Plan de Trabajo Anual - POA 2015,” Elecgalapagos, Tech. Rep., 2015. [Online]. Available: http://www.elecgalapagos.com.ec/pdf2015/KO7/Plan%20Operativo%20Anual%20-%20-POA.pdf

[29] “Perspectiva y Expansión del Sistema Eléctrico Ecuatoriano,” CONELEC (Consejo Nacional de Eléctricidad), Tech. Rep., 2013. [Online]. Available: http://www.regulacionelectrica.gob.ec/wp-content/uploads/downloads/2015/12/Vol3-Perspectiva-y-expansi%C3%B3n-del-sistema-el%C3%A9ctrico-ecuatoriano.pdf

[30] I. Das and C. Canizares, “Fuelling Change in the Arctic – Phase II Renewable energy solutions for the Canadian Arctic,” 2016. [Online]. Available: http://assets.wwf.ca/downloads/full%5Freport%5Ffeasibility.pdf

[31] J. C. Sierra, “Estimating road transport fuel consumption in Ecuador,” *Energy Policy*, vol. 92, pp. 359–368, 2016.

[32] “Diesel Prices, US Gallon,” GlobalPetrolPrices, 2018. [Online]. Available: http://www.globalpetrolprices.com/diesel%5Fprices/

[33] “Registro Oficial,” Ministerio de Transporte y Obras Publicas, Tech. Rep. 386, 2013. [Online]. Avail-

able: http://www.obraspublicas.gob.ec/wp-content/uploads/downloads/2012/09/SPTMF%5Fresol%5Fcarga%5Fgye-galapagos.pdf

[34] "Ficha Informativa de Proyecto 2016 Proyecto Fotovoltaico en la Isla Baltra - Archipiélago de Galápagos. Líder," Secretaria de Planificacion, Tech. Rep., 2016. [Online]. Available: ftp://190.152.52.4/LOTAIP/planificacion/SEGUIMIENTO%20GPR%20OCTUBRE2016/PROYECTOFOTOVOLTAICOENLAISLABALTRA.pdf

[35] "U57," The Wind Power. [Online]. Available: https://www.thewindpower.net/turbine%5Fmedia%5Fen%5F460%5Funison%5Fu57.php

[36] V. Vélez-Vega, M. Cedeño-Gómez, and O. Almeida-Chinga, "Energía Verde para Galápagos," *Programa de las Naciones Unidas para el Desarrollo*, p. 10, 2016. [Online]. Available: http://www.ec.undp.org/content/dam/ecuador/docs/documentos%20proyectos%20ambiente/pnud%5Fec%20REVISTA%20ENERGIA%20VERDE%20PARA%20GALAPAGOS-ilovepdf-compressed.pdf

[37] "Supporting the Energy Revolution," VAISALA. [Online]. Available: https://www.vaisala.com/en/industries-innovation/renewable-energy-and-weather

[38] "La presencia vehicular en Galápagos, un tema preocupante," Consejo de Gobierno del Regimen Especial de Galapagos, Tech. Rep. 1, 2013.

[39] C. Álvarez-Bel, P. Pesantez-Sarmiento, J. Rodriguez García, M. Alcázar-Ortega, J. Carbonell Carretero, P. Erazo-Almeida, D. X. Morales Jadan, G. Escrivá-Escrivá, A. Carrillo-Díaz, M. A. Piette, R. Llopis-Goig, E. Peñalvo-López, V. Martínez-Guardiola, M. I. Trenzano-García, V. Vicente-Pastor, V. Orbea-Andrade, and J.-M. Clairand, *Análisis para la implementación de redes inteligentes en Ecuador - Metodología de Previsión de la demanda basada en redes inteligentes*, C. Alvarez-bel, Ed. Editorial Institucional UPV, 2016.

[40] J. Zerad, S. Riachy, P. Toussaint, J.-P. Barbot "Novel Phasor Transformation for Feedback Control Design of Induction Heating Systems With Experimental Results," *IEEE Trans. Ind. Electron.*, vol. 62, no. 10, pp. 6478–6485, 2015.

[41] O. Lucía, P. Maussion, E. Dede, and J. Burdío, "Induction heating technology and its applications: Past Developments, current Technology, and future challenges," *IEEE Trans. Ind. Electron.*, vol. 61, no. 05, pp. 2509–2520, 2014.

[42] J. Martínez-Gómez, D. Ibarra, S. Villacis, P. Cuji, and P. R. Cruz, "Analysis of LPG, electric and induction cookers during cooking typical Ecuadorian dishes into the national efficient cooking program," *Food Policy*, vol. 59, pp. 88–102, 2016.

[43] J. Martínez, J. Martí-Herrero, S. Villacís, A. J. Riofrio, and D. Vaca, "Analysis of energy, CO2 emissions and economy of the technological migration for clean cooking in Ecuador," *Energy Policy*, vol. 107, no. March, pp. 182–187, 2017.

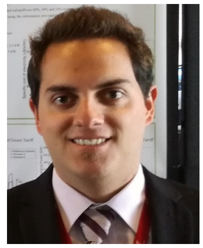
[44] "Las cocinas de inducción no serán para negocios de comida," El Mercurio. [Online]. Available: https://www.elmercurio.com.ec/444397-cocinas-de-induccion-no-seran-para-comercios-de-comida/

[45] "Annual Energy Outlook 2017 with projections to 2050," EIA, Tech. Rep. 8, 2017. [Online]. Available: https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf

[46] C. Stevanoni, Z. De Greve, F. Vallee, and O. Deblecker, "Long-term Planning of Connected Industrial Microgrids: a Game Theoretical Approach Including Daily Peer-to-Microgrid Exchanges," *IEEE Trans. Smart Grid*, vol. 14, no. 8, pp. 1–1, 2018.

[47] A. Khodaei, S. Bahramirad, and M. Sahidehpour, "Microgrid planning under uncertainty," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2417–2425, 2015.

[48] INEC, "Análisis de resultados definitivos Censo de Población y Vivienda Galápagos 2015," Tech. Rep., 2015. [Online]. Available: http://www.ecuadorencifras.gob.ec/documentos/web-inec/Poblacion%5Fy%5FDemografia/CPV%5FGalapagos%5F2015/Analisis%5FGalapagos%202015.pdf



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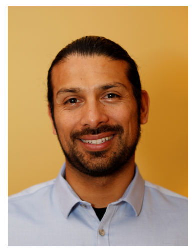

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