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Communications for Exploiting Flexible Resources in the Framework of Smart Grids in Islands

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Abstract

Although being among the least responsible for climate change, islands are in great threat due to it. The decarbonisation of the power system arises as a key factor to ensure adaptation and mitigation to it. Islands' characteristics make renewable electrification a challenge. Most islands are isolated systems with low levels of inertia that require stability for ensuring security of supply. Therefore, the potential of smart grids and flexible resources must be fully exploited to ensure a viable integration of renewable energy sources. In this vein, it is necessary to evolve the system including demand response, batteries and electric transport to increase the share of renewables. However, all these elements require a reliable communication architecture to be deployed. A communication architecture is hereby presented and applied to Galapagos for exploiting flexible resources. Different protocols have been selected to interoperate flexible resources integrated on the system. Each of them tries for each application to standardise and ensure the largest functionalities available. The deployment of smart grids in islands can reduce their carbon footprint as it is validated with a case study in Santa Cruz, Galapagos. This system proves to ensure the energy balance in a viable way, in technical, economic and environmental terms.

Keywords: smart grids, renewable generation, communication systems, flexible resources, islands, Galapagos

1. Introduction

Electric power business used to be a very traditional sector with a very well-established structure both in the physical and market layers. Depletion of fossil fuels, climate change, the boom of renewables and communications has forced a change in the ways in which the electricity is generated, consumed and traded. Traditional power systems were formed by large centralised generators, a very large and extended transmission grid to connect the generation and the load sites. Generation arrived to costumers through a final distribution grid, which was usually

operated in radial form to feed the large customers and small customers in low voltage (LV) [1]. However, the new time in the power sector are characterised by a large increment in the renewable generation. The main technologies are solar photovoltaic (PV) and wind generation. This generation can be concentrated in medium/large capacity plants or be very distributed. The so-called distributed generation (DG) is much smaller in size (commonly some tens to hundreds of kilowatts) and is usually connected to LV or medium voltage (MV). This generation can be owned by companies or individual customers that may also install some small generation. Moreover, the electrification of transport and the rise of information and communication technology are increasing the possibility to take advantage of customer's flexibility in the consumption by dynamically trading their demand response resources [2, 3].

This new power system paradigm is usually referred as the smart grid (SG) as it allows the integration of all these "active" elements (including customers) in the physical system (grid) and new trading mechanisms and markets (mainly retail) [4, 5]. The concept is gaining importance as the solution for the future power system [6]. However, it is essential a proper operation and control, which is intended to be automatic through SG controllers, using the resources offered by generators and customers directly or through intermediate agents such as load aggregators or generation aggregators, usually referred as virtual power plants (VPP) too [7].

The requirements for building these SG are as follows:

- **Reliability:** they have to be more reliable than the traditional power systems. This has to be accomplishing providing them with self-healing capacity.
- **Economic:** they have to reduce the cost of the electricity by integrating all available generation and new technologies like control, storage, etc.
- **Secure:** they have to be secure against physical attacks or cyberattacks.
- **Participation:** they have to give the consumer more options to participate in energy or other services markets.

To build this type of SG application, it is necessary to deploy a large number of elements (control centres, smart metering system, renewable control system, storage elements, etc.) and operate them in a synchronised and cooperative way so that the above-mentioned objectives can be achieved. In this sense, the information and communication technologies may be the bottleneck for a correct implementation of the SG paradigm. One of the most relevant problems is to establish reliable two-way communication systems between the distributed elements of the SG.

Normally, the digitalisation and communication layer has been studied on a very abstract level [8]. However, the implementation of such layers requires to be deployed at the application level to overcome the practical problems of smart grids. Thus, it remains essential to clarify and select the different protocols that need to be applied in a smart grid. A summary of them can be seen in [4]. Nevertheless, it is important to note that power systems and their communication systems remain in constant growing and evolution, and new protocols or upgrades of them are constantly appearing [9]. Therefore, the protocols that can be selected should tend to maximise the functionalities and ensure the maximum standardisation possible. To do so, the maximum number of functionalities and interoperability can be selected in order to better adapt the flexible resources potentialities to the communication

system. Moreover, the selection of standards also has to fulfil cybersecurity needs that enable a proper communication from the customer side to the system. Enabling a proper communication platform (such as internet) will remain essential to integrate distributed generation in the system.

Specifically, the transition to a more sustainable energy sector has gained importance in islands. Many islands are facing or will face severely the effects of climate change and are joining efforts to reduce their carbon footprints. However, their isolation and lower systems sizes represent a challenge to fully integrate volatile and intermittent renewables. Therefore, flexibility combined with renewable integration arises as a condition to make a viable transition from a fossil fuel-based system to a sustainable one. Thus, to capture all the benefits of renewable-based SG, islands need to deploy reliable communication systems designed for their particularities. Moreover, island scenarios are analogue to the cases of electrification of isolated rural communities, which are widely studied [10–12]. These systems tend to rely on hybrid systems with renewables in island to overcome the lack of electricity [13]. The deployment of renewables in island mode requires better coordination and communications to ensure the security, reliability and viability of the system under the stochastic nature of renewable energy sources [14].

This chapter aims to design an architecture communication to provide the communication and interactions design between the different agents. Second, this architecture model is applied to the Santa Cruz Island in the Galapagos archipelago. Here, the implications to have a smart grid with proper communications are detailed. In this vein, a year simulation is performed to show the results of the proposed architecture and highlight both economic and environmental benefits arising from the deployment of smart grids with large share of flexible resources.

The rest of the chapter is structured as follows: Section 2 outlines the communication characteristics and architecture required to implement a smart grid on islands. Then, Section 3 describes the Galapagos case of study under the scenarios suggested and includes the discussion of the results. Finally, in Section 4, some conclusions are drawn.

2. Communication architecture for exploiting flexible resources

The exploitation of flexible resources to boost the integration of renewables requires a proper communication architecture. In this section, the solutions that need to be applied at distribution level to integrate demand response, electric vehicles and distributed generation have been stated. Special attention is also put into the deployment of smart metres to ensure an advanced metering infrastructure that enables the correct operation of the smart grid.

In order to design the communication solutions, four different types of interactions based on the characteristics of the different participants have been considered. The first three types are implemented without human intervention (full automation), while the last one requires human intervention. Before describing these interactions, it is needed to explain the concept of actor. In this context, an actor is defined as any agent involved in the operation of the power system but not taking part as a consumer, storage or generator.

1. “Actor-generator/storage” communication

In this case, the system operator or the VPP remotely operates a generator or a group of them in real-time to provide secondary and tertiary control reserve or voltage control to the power system.

Reviewing the existing communication protocols used to operate generators remotely, there are a lot of options but it is proposed to use the protocol “IEC 61850”. It is expected that this protocol will be one of the most widespread solutions for integrating distributed energy resources (DER) in the distribution network when these resources are controlled by the DSO.

2. “Actor-consumer” communication

This communication is used to remotely change the electric consumption pattern of the customers that participate in a demand response programme in an orderly manner. In this regard, the exchange of data between an actor and a consumer includes different types of messages such as the transfer of an array of hourly prices (RTP), the customer acceptance of a DR event, the use of the direct load control (DLC), etc.

Regarding the proposed application protocol for this type of communication, the most widespread protocol related to demand response issues throughout the world is open ADR. One of its most important features is that it can be used to implement most of the demand response programmes existing nowadays. In particular, it is proposed to use the version 2 and the profile B due to the fact that it does not need to open any ports in customer’s firewall improving security aspects and avoiding a lot of problems during the initial hardware setting.

As an alternative to open ADR, the Open Charge Point Protocol (OCPP) is also proposed for managing the electric vehicle charging using the version 2.0. This protocol is the most widespread one in this specific field. Regarding the management of EV charging, it is important to highlight that this kind of flexible resources can be considered as a load or an electric battery depending on if V2G option is implemented or not.

3. “Actor-actor” communication

Apart from customers and generators, the rest of agents employ centralised management systems to perform their main activities. In this vein, it is very common inside the smart grid paradigm that all actors need to exchange information between them in real time. In the proposed communication architecture for islands, there is only one case where the TSO uses the flexible resources for operating the power system. In this case, the DR server of the TSO has to be able to send signals to the DSO, who acts as a DR aggregator. To this end, it is proposed to use open ADR 2.0b, in spite of this protocol was not developed to resolve this specific goal.

4. “Human operator-system” communication

Although the degree of automation is becoming higher and higher, there are some tasks that has to be already carried out by human operators (e.g., initial setting of systems). Moreover, graphical user interface (GUI) trends to be implemented as a web application in order to reduce the cost for improving the compatibility with the different versions of operating systems and other required applications such as database software, communication libraries DLL, etc.

According to all this, it is proposed the Hypertext Transfer Protocol Secure (HTTPS) to exchange information between human operators and centralised management systems. This protocol is an extension of the hypertext transfer protocol that improves security thanks to the integration of the Transport Layer Security (TLS), which encrypts bidirectionally all the packets exchanged between client and server.

2.1 Application to distribution automation

The standards and systems for the communication at transmission level among the different components (energy management system, generators, substations and large customers) are relatively well established due to the relevance of their performance in the overall reliability of the power system. In fact, before the development of smart grids, most of the investment in the electricity sector was made on the reinforcement of the transmission grid and improvement of the associated energy management system.

Regarding the communication requirements at distribution level, a lot of changes are necessary to evolve the existing infrastructure and systems into smart grids. The idea of making distribution systems more automatic is not new. In this regard, the utilities, along the last 30 years, have been trying to reproduce the successful EMS in transmission systems into distribution. What really happened is that a set of independent applications were developed in the distribution control centres (managed by the Distribution System Operator, DSO) at the feeder and substation levels. The communications required for these applications were usually implemented by using vendor-dependent protocols and by implementing different and independent data networks in the past, but the current trend is to minimise the number of proprietary communication implementations and use open, standard-based specifications.

According to that, the protocol IEC 61850, for controlling network elements from SCADA, and IEC 61850-2, for exchange information between control centres, is proposed to successfully implement the required communication at the distribution. Nevertheless, recently, new requirements have arisen at the distribution level due to smart grid implementation. For example, the adequate integration of new distributed energy resources such as distributed generation or storage, even if managed by virtual power plants, requires new communication features in the existing or new protocols. Additionally, it is important to highlight that due to the security problems associated with the cited protocols, it is necessary to consider the recommendations of IEC 62351 in order to increase the resiliency of the proposed solutions.

In addition to the specific standards commented above, a set of suggested communication standards for distribution automation applications are summarised below, based on the recommendations of the International Electrotechnical Commission (IEC, [9]):

- IEC/TR 62357 service oriented architecture (SOA)
- IEC 61970 common information model (CIM)/energy management
- IEC 61968 common information model (CIM)/distribution management
- IEC 61850 power utility automation. The following subsections are a result of special interest:
 - IEC 61850-7-420—Communication systems for Distributed Energy Resources (DER)—Logical nodes
 - IEC 61850-7-500—Use of logical nodes to model functions of a substation automation system
 - IEC 61850-90-2—Use of IEC 61850 for the communication between control centres and substations

- IEC 61850-90-6—Use of IEC 61850 for distribution feeder automation system
- IEC 61850-90-7—Object models for photovoltaic, storage and other DER inverters
- IEC 61400-25—Application of the IEC 61850 methodology for Wind turbines
- IEC 62351 security
- IEC 62056 data exchange for metre readings, tariffs and load control
- IEC 61508 functional safety of electrical, electronic, programmable electronic and safety related problems.
- IEC PAS 62746 interface between customer energy management system and power management system. Open automated demand response

2.2 Smart metres

The implementation of smart grids has to overcome all the problems that have encountered the utilities to enhance the distribution system. One key element in the communication chain in smart grids is the Advanced Metering Infrastructure (AMI) System that encloses all the elements to provide a reliable and secure communication to the most important partner in smart grids: the customer [15].

The main features of the AMI systems are:

- Smart metre, which is the frontier element with the customer, where bi-directional communication is implemented and where the smart metre may initiate a conversation with other agents in the smart grid. For example, it may send a black out (no supply voltage signal) before the metre goes off.
- The smart metres must be configurable in remote mode so the parameters of customer facility (for example, the protection settings) may be remotely changed without needing to go physically to the customer site.
- The smart metres may also be used as the gateway of customer network for other distribution management systems (Home Area Network, HAN, in residential customers).
- The smart metres have not been considered suitable for demand response implementation, as discussed later, because the possible delays and latencies introduced by other processes running in the metre.
- Another basic component, which is complementary to the AMI system, is the measurement data management (MDM) system that is an application responsible for the measurement data consistency and coherency checking as well as for the preparation of this data for further applications: commercial or technical.

According to what has been reviewed so far, it is clear that there are two main issues in developing smart grid communication structures and systems:

interoperability and cybersecurity. Interoperability may be warranted by using the adequate non-vendor protocols for communication, whereas cybersecurity may be improved considering the recommendations of standards devoted to this issue (e.g., IEC 62351).

2.3 Application to electric vehicles

Integration of EVs on the system is being widely studied due to the interest of decarbonizing transport [16]. In this regard, the interoperability and necessity to charge and discharge EVs is a topic of interest due to the large number of existent studies [17–19]. The proposed standards for charging electric vehicles are mainly three. On the one hand, open ADR is proposed to manage the EV charging of commercial and residential customers, especially in the case of wall-box charging stations due to the requirement of standardising the protocols for controlling loads at residential and small commercial customers. Their specifications are described in “Section 2.4”. The IEC 61850 standard has also been studied for implementing the harmonisation of charging protocols of EVs [20].

Finally, “Open Charge Point Protocol” (OCPP) is proposed for public charging stations. This is an open and interoperable communication standard based on JSON over Websockets, including compression for data reduction what facilitates the interchange of information between EV centralised management system and the charging stations.

This protocol has been considerably improved in version 2.0 with extended functionality related to smart charging such as direct smart charging inputs from a centralised management system to a charging station or just with a local controller and supporting smart charging based on ISO15118.

OCPP 2.0 supports around 120 use cases that are integrated into 16 blocks according to different functionalities. These are completely described in [21] and are summarised below:

- a. Security
- b. Provisioning
- c. Authorization
- d. Local authorization list
- e. Transactions
- f. Remote control
- g. Availability
- h. Reservation
- i. Tariff and costs
- j. Metering
- k. Smart charging
- l. Firmware management

- m. ISO 15118 certificate management
- n. Diagnostics
- o. Display message
- p. Data transfer

Although there are several interesting functionalities for the deployment of smart grid, smart charging can be considered the most relevant for its impact on the feasibility of the proposed solution. The capacity of smart charging implies that a centralised EV charging management system gains the ability to influence the charging power or current of a specific electric vehicle or the overall energy consumption of an entire charging station during a period of time. Therefore, an external system has the possibility to set a charging profile as a limit of overall energy consumption of each charging station or group of them, what can be suitable to improve distribution network operation (network restrictions, balancing, loss reductions, etc.). This protocol is enabled to implement V2G applications.

2.4 Application to demand response

As commented above, the communication protocol “OpenADR” has been chosen since it has been identified as the best standard procedure for this application. Currently, it is the most used protocol to implement DR actions in power systems [22].

The OpenADR 2.0 standard includes two profiles:

- Profile A (OpenADR 2.0a). It has been designed for low-end embedded devices to support the basic services of demand response and markets.
- Profile B (OpenADR 2.0b). It has been designed for high-end embedded devices and it includes feedback to consumers as a response to events/data reports, present and futures.

The “OpenADR Alliance” has developed the procedures and necessary tools for the certification of products working with such protocol:

- The technical specifications for different profiles
- The documents establishing the characteristics that should be mandatory for each profile
- The testing plan; the certification documents
- Finally, the tools to perform the certification tests that may be used by third parties to check their products

A new concept, introduced in OpenADR 2.0, is the capacity to support two types of communication nodes: “Virtual Top Node” (VTN) and “Virtual End Node” (VEN).

The VTN represents a server that published and transmits OpenADR signals to final devices or other intermediate servers. The VEN is a client, a building energy management system (BEMS) or terminal device that accepts OpenADR signals

from the VTN and responds to them. A final node may simultaneously be VTN and VEN. OpenADR signals are sent through standards based on internet protocols (IP) such as “Hyper Text Transfer Protocol” (HTTP) or “XML Measuring and Presence Protocol” (XMPP).

Information on a new event is contained in five parts:

- Event description: general metadata about the event
- Active period: starting time and total duration
- Event signal: interval data for the event
- Reference line for the event: interval data for the reference line
- Objectives: objective resources of the event (single VEN, defined VEN group, type of device, service area, type of resource, etc.)

Regarding security, open ADR uses a public key infrastructure (PKI) in order to provide:

- Authentication
- Confidentiality
- Integrity of transmitted data

There are two security levels between communications:

- Standard security: TLS with certificate interchange between server and client
- High security: it adds to standard security the utilisation of digital signatures for the XML data, so that the risk to reject information is reduced

Certified products should be provided with standard security, being optional the incorporation of high security.

According to the loads that need to be controlled and their communication needs, four different configurations for implementation have been considered:

- Connection to residential and small commercial consumers
- Connection to residential and small commercial consumers through a graphic user interface (GUI) on the cloud
- Connection to residential and small commercial consumers through an BEMS
- Direct connection to industrial and commercial consumers
- Aggregator model

Among other existing programmes, which may be implemented by means of open ADR, the following examples can be found:

- Residentia

- “Save Power Day” (SPD)
- “Summer Advantage Incentive” (SAI)
- Commercial and industrial
 - “Demand Bidding Program” (DBP)
 - “Summer Advantage Incentive” (SAI) also known as “Critical Peak Pricing” (CPP)
 - “Capacity Bidding Program” (CBP)
 - “Aggregated Managed Portfolio” (AMP)
 - “Base Interruptible Program” (BIP)
 - “Real Time Pricing” (RTP)

Apparently, the requirements for the communication between a DR requester (system operator, DR aggregator, etc.) and a DR provider are linked to the implemented type of DR programme. In this regard, a basic set of DR programmes was proposed to try to maximise the benefit of the potential flexibility of each type of flexible resource. They were classified into two groups depending on the degree of automation of the solution that is defined as:

- *DR programmes oriented to semi-automatic control systems*: customers receive a notification at least 1 hour before the starting time of a DR event, and they should set up their local control systems to implement the DR action on time. Some examples of this type of DR programmes are known as “Traffic lights” (CPP) more suitable for residential customers or “dynamic pricing (RTP)” for industrial customers. The strong point of this type of programmes is that there is no need to install additional hardware in the customer facilities, except from installing smart metres that it is necessary to hourly collect the energy consumption in real-time. However, the drawback is a lower percentage of customer who reacts to these kinds of signals and the lack of accuracy for implementing the response.
- *DR programmes for automatic control systems*: customer’s resources are directly controlled by other agent, but there is a clear definition of how this control has to be implemented. In this regard, two types of signals can be received by the local control system to implement a DR event: a price signal or a power set point. Regarding the first type, it is proposed to use auto-DR programmes or fast DR programmes depending on the reaction time of each resources to implement the change of pattern that can be used to provide secondary reserve or primary reserve, respectively. On the other hand, it is proposed to use direct load control for large flexible resources due to the need of being more accurate in the implementation of DR events.

Finally, according to the proposed model, customers may have installed generation plants with an installed power lower than 100 kW with additional electric batteries that might be remotely controlled using open ADR as the explained flexible resources due to they have the same network conditions.

Regarding all these DR programmes, it is not recommended to use the smart metre as a gateway to communicate with local control systems and devices due to possible delays and latency problems in the communication network as mentioned above.

2.5 Application to distributed generation

Distributed generation can be defined as generation that is small, disperse and connected to the distribution grid [23]. Regarding VPP, it can be considered as the agent that coordinates small and disperse generation to perform as a single entity.

The kind of distributed energy resources depends on the installed power and has been characterised and the communication requirements settled according to the following three groups:

1. $P_{inst} < 10 \text{ kW}$. In this case, there are no direct control actions on devices, being just necessary to install a smart metre.
2. $10 \text{ kW} \leq P_{inst} < 100 \text{ kW}$. In this case, the VPP is responsible for the management, so that basic control (on/off) has been considered.
3. $P_{inst} \geq 100 \text{ kW}$. For this kind of facilities, aggregation into a VPP is proposed in order to offer ancillary services, as well as voltage control to the TSO. This requires that distributed generators must be able to be controlled as if they were conventional generators, with PQ set points.

2.5.1 DG of $10 \text{ kW} \leq P_{inst} < 100 \text{ kW}$

Control requirements for this kind of generation, according to the conceptual design, are low. Therefore, just the possibility of disconnection in case it is necessary for the TSO has been considered. According to these requirements and considering that control orders would be submitted by the aggregators, the utilisation of the protocol open ADR 2.0b simple XMPP in Push mode has been considered for connection and disconnection. In Option 1, the installation of a multiprotocol communication gateway is proposed in order to connect to the SCADA (local control), or to a programmable logic controller (PLC). In Option 2, the local control system may have a SCADA able to receive messages according to the open ADR protocol by means of an additional software module. Both solutions consider the access to the Internet by means of any available technology, as shown in the figure:

In that case, devices to be installed would be the following:

Additionally, the installation of smart metres should be considered in the same rate as the communication gateway devices.

2.5.2 DG of $P_{inst} \geq 100 \text{ kW}$ (VPP)

Control requirements for this kind of generation would be similar to those expected from a conventional generator. In case of photovoltaic power plants, inverters will be responsible for incorporating this management option. Such configuration would allow omitting the SCADA, which may be substituted by a RTU able to use the IEC-61850 protocol for monitoring and controlling the inverters by means of PQ signals.

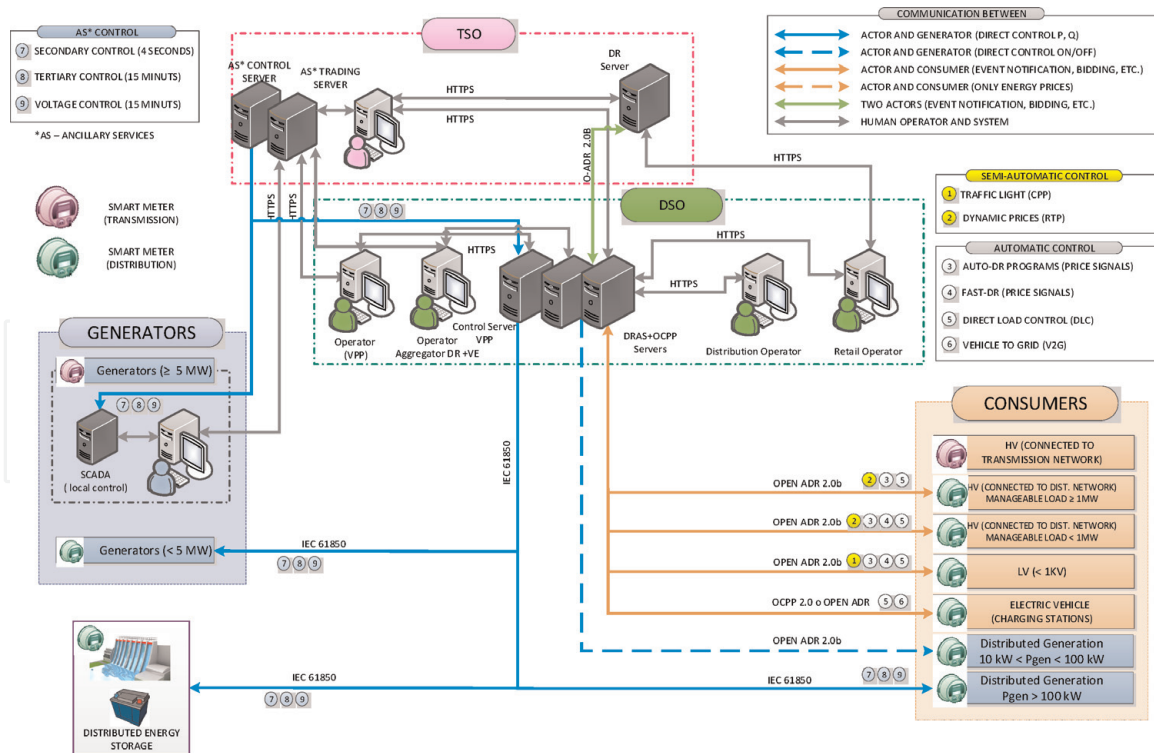


Figure 1.
Proposed communication architecture in Galapagos.

The same protocol IEC 61850 will be used to manage distributed storage such as batteries because in this particular case it is proposed to be performed by the DSO (Figure 1).

3. Case study of Galapagos

The proposed architecture is applied to the Santa Cruz Island, located in the Galapagos archipelago (Ecuador). These 21 islands are located 1000 km West of Ecuador's mainland (Figure 2). Approximately 26,000 people inhabit them; being Santa Cruz Island the most populated one of them. Notwithstanding its bio reserve protected status and an increasing concern about its preservation, tourism keep growing. From 1990 to 2015, visitors have doubled every 5 years [24], increasing the pressure over natural resources, especially electrical power demand. In this context, a transition to a renewable and sustainable energy mix for the archipelago is crucial to safeguard it [25]. Thus, the Ecuador government launched a Zero Fossil Program for Galapagos in 2007 to achieve a zero emission goal [26]. Nevertheless, this programme raises several technical difficulties due to the small size of the archipelago's mini grids and their low capacity to absorb and integrate renewables. The implementation of a smart grid architecture in Galapagos is aligned with one of the main energy and sustainability challenges that small islands and systems are facing currently, energy dependence, reliability and climate change [27]. Moreover, it boosts the efforts that are being performed to improve the current efforts to integrate renewables in small islands [28, 29].

3.1 Electricity system of Santa Cruz

Santa Cruz operates as an isolated mini grid coupled with the Baltra Island, where the island's airport is located. The island's electricity is mainly generated

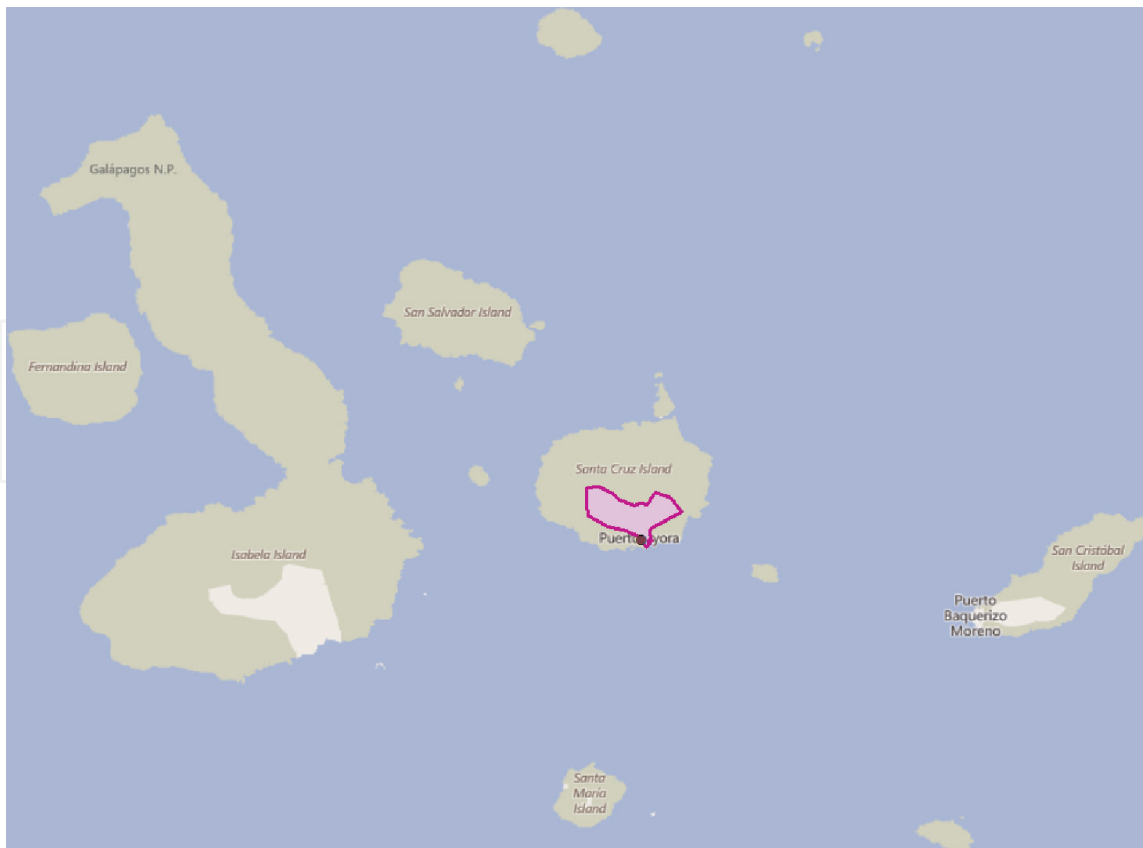


Figure 2.
 The island of Santa Cruz in Galapagos.

with diesel that has to be imported from mainland. Currently, 2.25 MWp of wind power and 1.5 MWp of solar PV are installed in the island. However, both of them combined did not cover more than 12% of the total electricity demand in 2017. The main consumption occurs in the urban area and has the potential to become flexible and integrate renewables on it. The existing distribution network can be seen in **Figure 3**.

Due its geographical isolation, Galapagos and particularly Santa Cruz represent an extreme case to analyse the viability of the proposed architecture and its replicability. Thus, the transformation of Santa Cruz into a smart grid as the one proposed in this chapter offers several benefits at a reduced cost. The proposed architecture can be easily implemented in Santa Cruz, facilitating renewable energy integration and improving the system performance.

3.2 Simplified model

In order to assess the potentials of the smart grid, we propose a simplified *ex post* energy balance with historical and modelled data. The first requirement in the analysis is to fulfil at any time step the energy balance presented.

$$P_t^D + P_t^L = \sum_g P_{gt} + \sum_g \Delta t * f r C_{gt} \quad (1)$$

The generation in the smart grid with high penetration of renewable energy source scenario, the performance of the existing wind turbines and the solar farm; and the measured wind speed at hub height are used to linearly model the performance of the newly integrated renewable energy sources. Thus, the wind has been modelled with wind speed levels at 10 m. These have been corrected to get them at

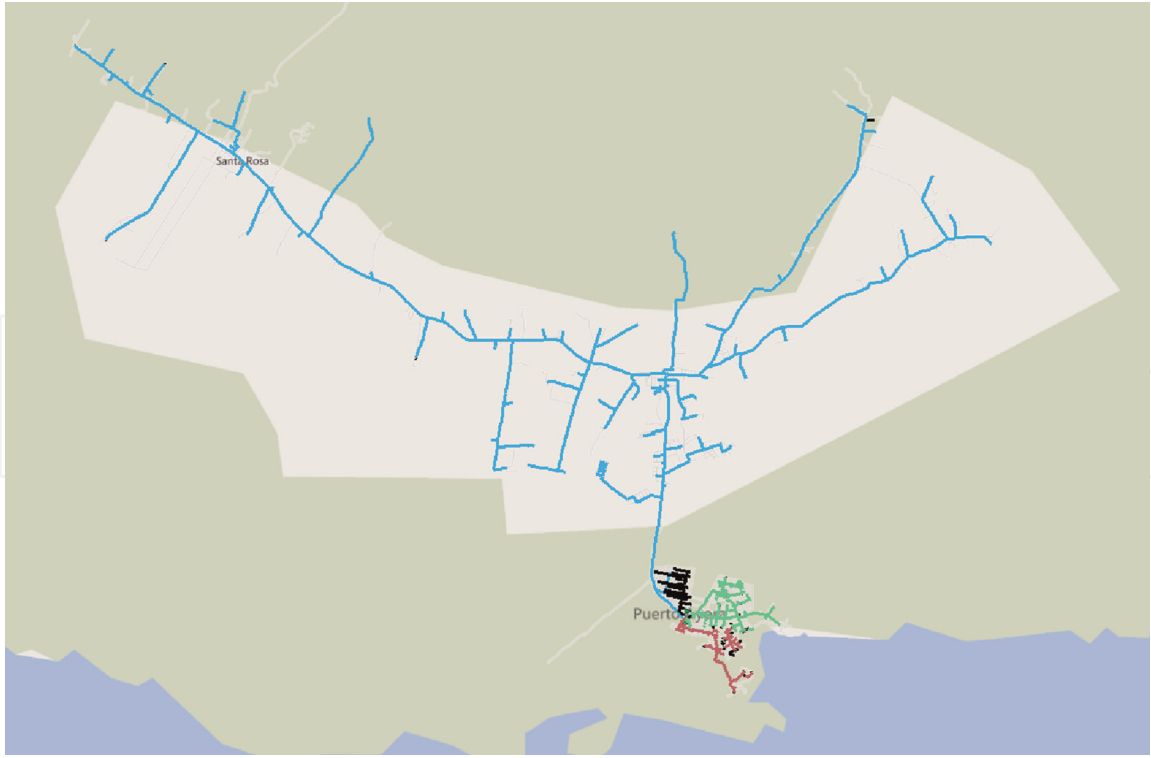


Figure 3.
Medium voltage distribution system in Santa Cruz [30].

80 m with a logarithmic correlation and then the wind production curve has been applied. The solar PV power has been calculated as a correlation of the actual production and a coefficient to increase the PV capacity. And at any time step, the system has to be inside the maximum and minimum capacity levels.

$$P_{gt}^W = \frac{1}{2} \rho \eta_t R^2 \pi u_t^3 \quad (2)$$

$$\underline{P}_g \leq P_{gt} \leq \overline{P}_g \quad (3)$$

The thermal capacity has been modelled as the difference between demanded electricity and losses. Thus, the existing thermal generator acts in a flexible manner to adjust generation to demand as it currently does.

$$P_t^D + P_t^L - \left(\sum_g P_{gt}^{PV} + \sum_g P_{gt}^W + \sum_g \Delta t * fr_{gt} \right) = \sum_g P_{gt}^T \quad (4)$$

The flexible resources such as demand response and electric vehicles have been characterised as batteries. This is a common model simplification [8, 9]. The flexible resources have a state that is among a maximum and minimum capacity and is represented by its state in the prior time step plus the charge or discharge ratio during the time period. Moreover, the charge and discharge ratios also have limits. Thus, these elements are modelled as:

$$SOfr_{gt} = SOfr_{g(t-1)} + \Delta t * frC_{gt} \quad (5)$$

$$\underline{SOfr}_h \leq SOfr_{gt} \leq \overline{SOfr}_h \quad (6)$$

$$\underline{frC}_h \leq frC_{gt} \leq \overline{frC}_h \quad (7)$$

No network constraints have been considered since it does remain out of the scope of this work. However, the costs associated to the increase on the distribution lines due to the new generation have been included in the installation costs.

The environmental analysis has been performed according to the emissions associated with electricity generation. Thus, the emissions have been calculated with emission factors associated with each type of fuel.

$$\text{GHGe} = \sum_i \text{EF}_i * q_i \quad (8)$$

Finally, the analysis of the scenarios has been done with two basic economic indicators, the net present value (NPV) and the return over investment (ROI):

$$\text{NPV} = \text{Inv} + \sum_y \frac{CF_y}{(1+j)^y} \quad (9)$$

$$\text{ROI} = \frac{\text{NPV}}{\text{Inv}} \quad (10)$$

3.3 Description of the scenarios

To study the benefits that arise from the smart grid deployment, three scenarios have been analysed and compared: business as usual, current status with smart grid and smart grid with high penetration of renewable energy sources.

First, the current situation of the system is taken as the “Business As Usual” (BAU) scenario. The system performance in 2017 is taken as the base for this scenario. As mentioned above, this scenario is characterised by 1.5 MW of solar PV, 2.25 MW of wind power and a large reliance on thermal generation to cover almost 90% of the electricity consumption. Currently, some wind production is curtailed due to the low flexibility of the system.

The second scenario is named “Smart Grid”. The smart grid scenario is able to integrate all the wind generation that is currently curtailed thanks to the flexibility given by the system installed in this scenario and the better information channels implemented. This flexibility capacity is obtained from demand response resources, the VPP and the management of the EV charging stations installed. Their capacities have been estimated as percentages of the total demand and the study of the flexibility options that arise from them. The aggregator manages these programmes, which provides a flexibility that afterwards is sold to the VPP. Then the VPP manages this flexibility to provide firm power to the grid. Regarding the capital cost required to install the smart grid, the prices here summarised have been obtained from [30]. Different international smart systems and automation companies proposed solutions. **Table 1** presents a summary of the average prices communicated by them.

The third scenario is named “Smart Grid + Renewables”. The same smart grid as the one proposed in the second scenario is implemented. Moreover, the integration of new renewable energy capacity has been optimised to obtain the maximum share of renewable energy generation without curtailment. This capacity can be integrated due to the increase in flexibility associated with the smart grid. Demand response programmes and an optimisation of the system performance allow the system to largely increase the share of renewables in the electricity mix. For this scenario, the capital cost of the newly installed generation has been retrieved from 2017 IRENA’s world averages [31]. Prices are assumed to be 1.388 and 1.477 \$/kW for solar PV and onshore wind, respectively. With the current grid infrastructure and the flexibility that the smart grid systems provide, the Santa Cruz Island could

Element	Cost
Smart metering	\$ 318,200
Demand side management ¹	\$ 950,000
Smart grid control	\$ 150,000
Virtual power plant	\$ 450,000
Total	\$ 1868,200

¹The DSM includes all the infrastructure and equipment to implement DR.

Table 1.
Smart grid costs.

Technology	Cost
Smart grid	\$ 1868,200
Solar PV	\$ 4,302,800
Wind	\$ 3,323,250
Total	\$ 9,494,250

Table 2.
Smart grid with high penetration of renewable investment cost.

absorb renewable energy generation from up to 4.6 MW of solar PV and 4.5 MW of wind power. Thus, 3.1 MW of solar PV and 2.25 MW of wind power could be installed. According to the abovementioned prices, the total capital cost required for this scenario is (**Table 2**):

The analysis and modelling of the scenarios has been performed to fulfil power and energy balances in 10 minutes time steps. The simulations have taken into account the real data from Santa Cruz Island. The data used has been electricity demand and solar PV, wind and thermal generation data. Whenever wind production has been curtailed, the theoretical power values of the wind turbine have been calculated with the power curve characteristic and the 10-minute wind speed average at the wind turbine's hub height data.

Finally, regarding the economic analyses, different data from the country has been used. Despite the diesel end-price in Ecuador is subsidised, a non-subsidised price of \$1.08 per litre is used to analyse the economic benefits of the implementation. This price is used according to the local ratio where the subsidies cover 75% of the mentioned fuel, and the current prices at April 2018 are \$0.27 per litre in Ecuador and \$1.04 per litre as the World's average [32]. The cash flows have been calculated for the smart grid and smart grid + renewables scenario as the associated savings of not using the fuel. For both scenarios of smart grids, the parameters assumed to evaluate the investment are as follows: the lifetime period has been considered 10 years; the cash flows have been assumed constant during this period; the economic benefits are based on a yearlong energy balance simulation and the interest rate used has been 8%. For the environmental analysis, an emission factor of 2.67 kg CO₂ per litre of diesel has been used after the U.S. EPA [33].

3.4 Discussion

In order to assess the potentialities of each of the proposed scenarios, the business as usual scenario is presented in the next **Figure 4**. As it can be seen, the

demand is mainly covered by thermal generation as renewable generation just covers about 10% of it. Moreover, as it has been stated part of the wind power generation was curtailed.

The smart grid scenario deploys the above-explained infrastructure. This new communication infrastructure improves the efficiency of the system and the renewable integration. The smart grid with flexible resources allows improving the capacity factor of the wind production from 13 to 26.3% with an improved information system that allows managing the energy production and optimise the renewable output. The improvement and digitalisation of the current grid infrastructure will allow a reduction of 24 kTnCO₂. The required investment for the implementation of the proposed smart grid architecture would be \$ 1868 million, which will be rapidly recovered due to the economic savings obtained from fuel savings. The payback would be lower than 2 years, the net present value will amount benefits up to \$3.7 million. This shows how the investment would be not only profitable but highly valuable in economic terms with a Return Over Investment (ROI) of 197.78% in 10 years. Moreover, the installation of the smart grid systems will pave the way for future investments and newly renewable energy generation (Figure 5).

In the third scenario, new solar PV and wind capacity are installed in order to maximise the share of renewable energy production. The smart grid architecture provides the needed flexibility to integrate generating facilities characterised by their stochastic nature. This integration allows the Santa Cruz Island to reduce more than 46% of the current emissions associated to electricity production. Besides the environmental benefits, the economic benefits of this action would be positive too. The installation of new capacity requires a high initial investment, which will be recovered in less than two and a half years. Moreover, due to the large diesel demand reduction, the benefits associated with this project would add to \$12.4 million. Thus, being a profitable investment with an ROI of 130.15% (Figure 6).

To sum up the scenarios, the following figure shows a comparison among the energy balances of the presented three scenarios. As it can be seen, the current situation shows a system with large diesel consumptions associated to thermal generation while renewable energy has to be curtailed. The smart grid scenario provides an improved picture; the communication system associated with flexible

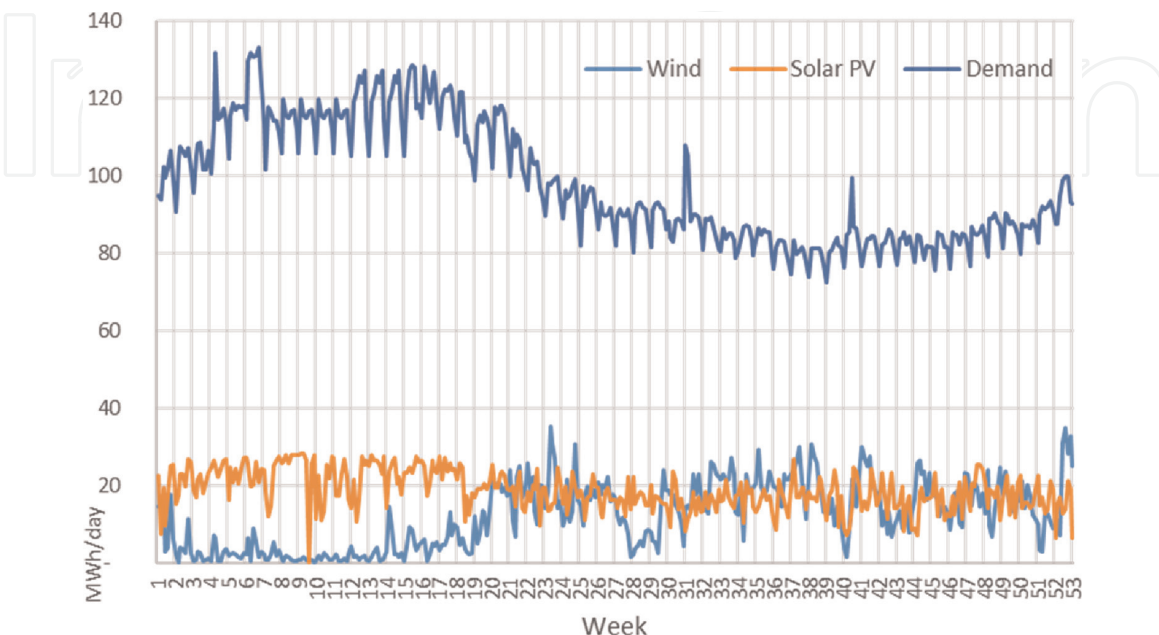


Figure 4.
Daily energy balance 2017. BAU scenario. Own elaboration based on [30].

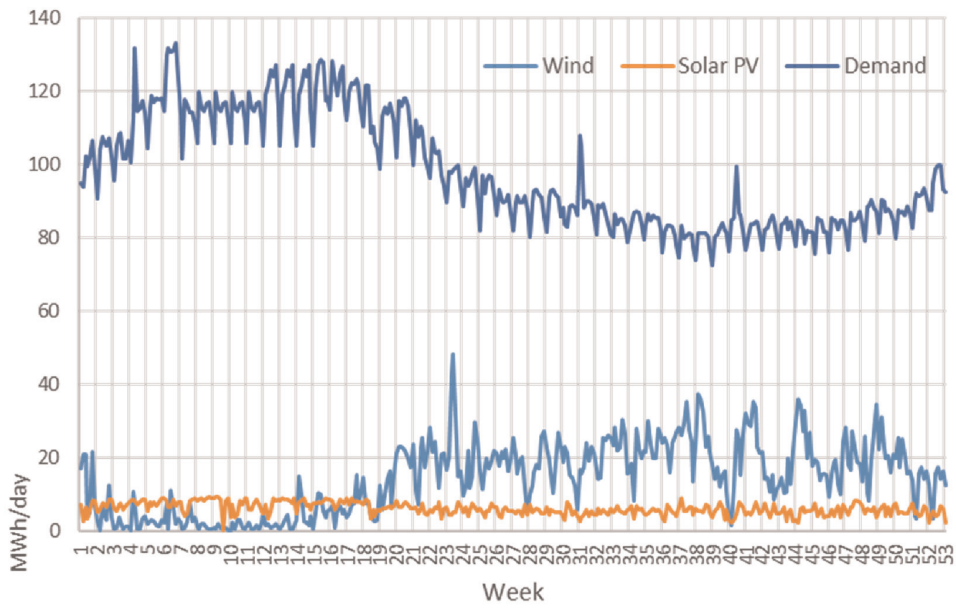


Figure 5.
Daily energy balance 2017. Smart grid scenario.

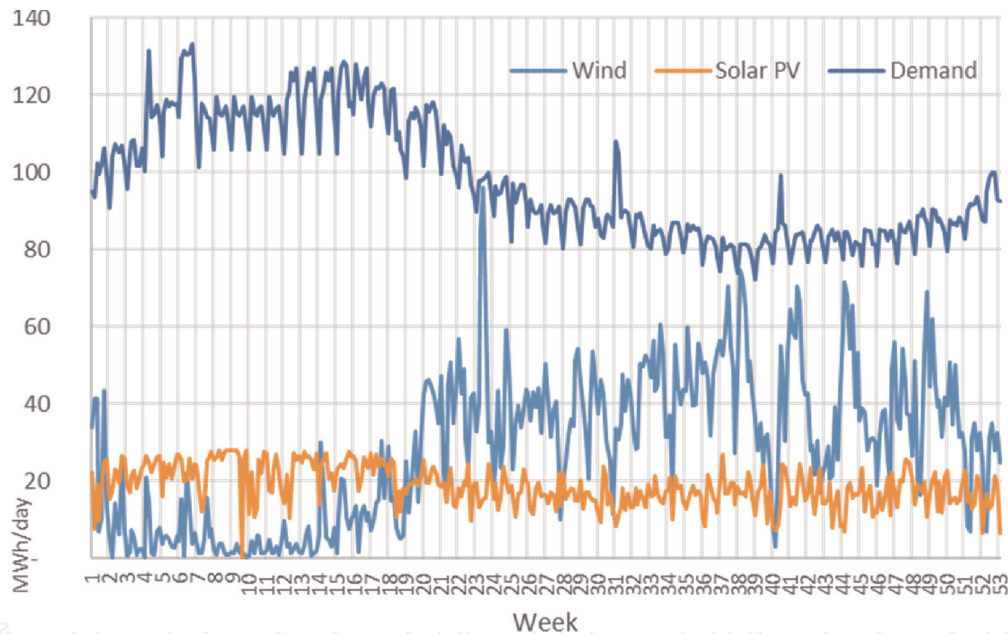


Figure 6.
Daily energy balance 2017. Smart grid + renewables scenario.

demand allows a total integration of the renewable generation. Finally, the third scenario depicts an energy mix with a share of renewables that accounts almost up to half of the total generated energy (Figure 7).

The variations between scenarios in renewable integration are associated with economic expenses and environmental impacts. In the BAU scenario, the Ecuadorian government is spending approximately \$9.3 million a year just in diesel consumption. Moreover, this scenario is far away from the Galapagos Zero Emissions target with more than 224 kTnCO₂ emitted during 2017. Even though the 2.25 MW of wind and 1.5 MW of solar PV that are currently installed, the share of renewable energy generation in 2017 accounted just up to 11.2%. However, the renewable energy production could be optimised with the proposed smart grid implementation and the installation of new renewable capacity.

Regarding flexible resources, the residential, EV and commercial demand response centralised in the role of the aggregator allow the system to manage up to

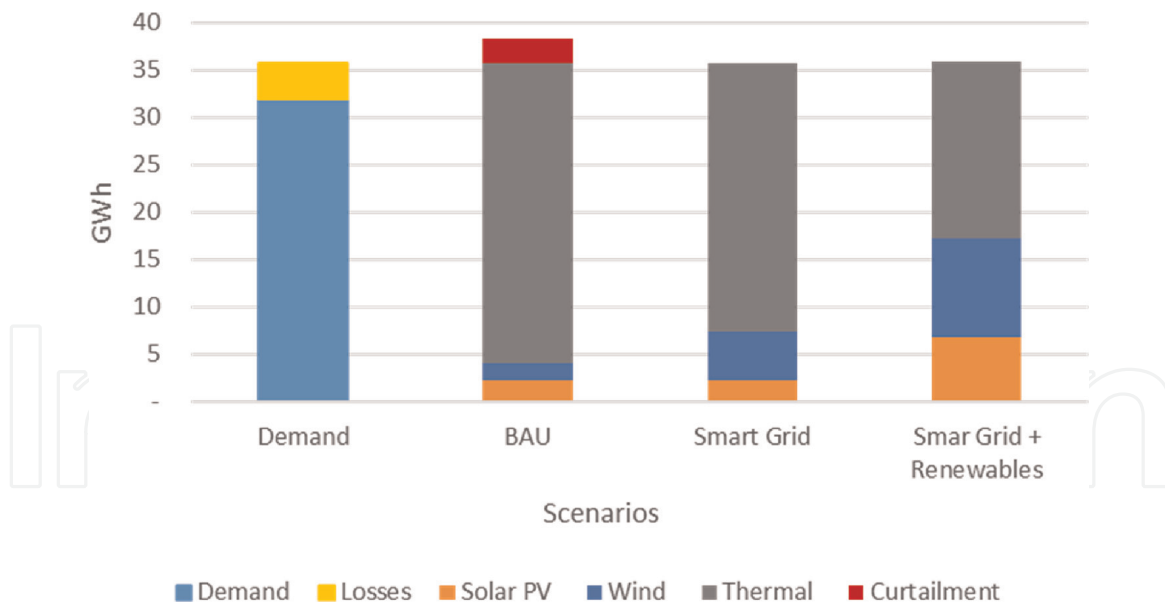


Figure 7.
 Scenario's energy balance.

634 MWh/year. From this amount, EVs provide 50% of the flexibility. Commercial consumers provide 40% of the flexibility. The commercial DR is used 500 hours a year with an average flexibility of 250 kW. On the other hand, residential DR is only used during 85 hours a year, being these ones the most critical for renewable integration. Thus, commercial flexibility is used 10.5% of the time while the residential flexibility is used just 1% of the time. This will generate lower distortions to actual residential consumption patterns. Something may help the social acceptance of the project.

The results of the three scenarios proposed are summarised in **Table 3**:

As it can be seen, the payback of investing in the proposed architecture would have a payback lower than 2 years and a ROI of 198% while reducing 24 k TnCO₂.

Element	Scenario		
	Business as usual	Smart grid	Smart grids + renewables
Solar PV (MW)	1.50	1.50	4.60
Wind energy (MW)	2.25	2.25	4.50
DR commercial (MW/MWh)		1.0/4.1	1.6/4.1
DR residential (MW/MWh)		0.5/1.0	0.8/1.0
EV (MW/MWh)		0.9/1.6	0.9/1.6
RE integration (%)	11.2	20.3	47.5
Diesel consumption (m ³)	8609	7688	4991
Emissions (kTnCO ₂)	224.7	200.6	130.3
Investment (M\$)	—	1.87	9.49
Annual savings (k\$)	—	0.99	3.91
Payback (years)	—	1.90	2.43
NPV (M\$)	—	3.70	12.36
ROI (%)	—	197.8	130.2

Table 3.
 Scenarios' results.

The inclusion of new agents as the VPP and the DR aggregator provides to the power system more flexibility that allows a larger integration of renewables that could increase from 11.2 to 47.5%. Both alternative scenarios present environmental and economic benefits. On the one hand, the implementation of the smart grid with flexible resources has a lower payback, while the scenario smart grid + renewables presents more benefits on the long run due to the significant reduction of the diesel consumed. This latter scenario shows also a larger energy security due to the lower needs in diesel transportation and storage to the islands.

4. Conclusions

This paper presents a communication architecture that allows efficient communication flows to fully exploit the potential of flexible resources in order to accommodate larger integration of renewable energy sources. Based on the different protocols and features of smart grids, the necessities have been characterised, specially the inclusion of flexible resources such as demand response programmes, the electric vehicle, storage and distributed generation.

The communication architecture selected for Galapagos has proven to be a feasible solution in both technical and economic terms. The protocols selected have focused on maximising the functionalities due to their higher levels of development. First, the IEC-61850, following the security recommendations of IEC-62351, was selected as the main standard to control distributed energy resources (connected to the distribution grid) considering the use of distributor's private data network. Second, open ADR 2.0 was selected to ensure a secure and reliable implementation of the demand response among consumers in order to control loads and small renewable generation inside the customer facilities. Finally, the OCPP was selected as the protocol to manage the charge/discharge of EV batteries due to its large catalogue of functionalities. These two solutions are proposed to be implemented using the Internet network for reducing the required investment.

The ecological value of Galapagos is undoubtable and a transition to a sustainable energy system is mandatory. However, their particular orography and isolation generate to Galapagos Islands' grids a difficult challenge to achieve renewable energy integration. For this reason, a case study in the island of Santa Cruz has been studied. The implementation of a smart grid with the proposed architecture in Santa Cruz can help the island to perform an effective transition to become zero fossil fuel. A 1-year simulation in the third scenario highlights the importance of flexible resources to integrate renewable generation. Nevertheless, the results show that the implementation of a smart grid could not only immediately improve Santa Cruz power system emission factor and efficiency but will also allow future integrations of renewables.

As a conclusion, the proposed smart grid architecture proves to be valid and efficient in both economic and environmental terms. The inclusion of flexible resources on the system proves to be a valuable asset to help integrating renewables. This can be done thanks to the aggregation of the individual responses and the exploitation of electric vehicles, thus showing the importance of managing the flexibility of the system.

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Conflict of interest

“The authors declare no conflict of interest.”

Nomenclature

Indexes

t	index of time periods
g	index of generation elements
i	index of fuel type
h	index of flexibility elements
y	index of years

Parameters

ρ	air density
R	radius
\overline{P}_g	maximum generation capacity of the generator g
\underline{P}_g	minimum generation capacity of the generator g
\overline{SOfr}_h	minimum state of charge of the flexible resource h
\underline{SOfr}_h	maximum state of charge of the flexible resource h
\overline{frC}_h	maximum discharge capacity of the flexible resource h
\underline{frC}_h	minimum charge capacity of the flexible resource h
EF_i	emission factor of the fuel type i

Variables

$GHGe$	green house gas emissions of the scenario
P_t^D	electricity demand during the time period t
P_t^L	electricity losses during the time period t
P_{gt}	electricity generated by generator g during the time period t
P_{gt}^{PV}	electricity generated by PV generator g during the time period t
P_{gt}^W	electricity generated by wind generator g during the time period t
P_{gt}^T	electricity generated by thermal generator g during the time period t
$SCfr_{ht}$	state of charge of the flexible resource h during the time period t
frC_{ht}	charge/discharge power of the flexible resource h during the time period t
q_i	quantity consumed during the year of the fuel type i
CF_y	cash flow during the year y

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