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Research Paper

Smart energy system approach validated by electrical analysis for electric vehicle integration in islands

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ABSTRACT

This article discusses the integration of renewable energy sources in islanded energy systems, focusing on electrification of the transport sector and highlighting the challenges that are faced. The proposed method comprises different steps. First, the energy system is analyzed using the Smart Energy Systems concept to identify high renewable energy scenarios. Then, the power system is evaluated to ensure compliance with security and stability requirements. The method innovatively combines an overall energy system analysis, from an energy planning perspective, with more detailed power system analyses, where the power balance at each instant is the main item of interest rather than the energy balance. The study, applied to Gran Canaria (Canary Islands, Spain), demonstrates that 100% electrification of passenger cars with renewable energy sources is the optimal scenario, resulting in reductions of 45.86% and 45.1% in oil consumption and CO_2 emissions, respectively, compared to the reference scenario. In addition, in these optimal conditions, there would be a 29.9% reduction in the total annual costs of the energy system and a 13.81% reduction in the total energy required to supply it. The stability analysis that was undertaken confirms that the system can handle a significant electric vehicle load and high renewable energy production without excessive load shedding.

1. Introduction

The integration of renewable energy sources (RES) into energy systems has significant implications for the economic development and the living conditions of local communities [1]. There is a clear consensus on the importance of promoting the use of RES [2] despite the challenges they create due to their inherent intermittency and variability, which can impact network voltages and the system frequency of electric power systems [3].

To address these challenges and increase the share of RES, integrated energy planning strategies have been proposed [4]. One such approach involves electrifying the land transport sector [5]. This is particularly relevant for islanded energy systems where dependence on externally supplied fossil fuels is high [6]. Compared to continental regions, islands tend to face higher costs for transportation, communication, and energy [7]. Additionally, the typically small size of islanded energy systems is a key barrier for the penetration of renewable energy solutions [8]. However, islands usually have a high potential for electricity generation from locally available RES [9]. Islands have thus gained increasing interest as a novel focus for transition planning research, particularly with respect to transport sector electrification [4].

There is a diverse range of computer software available for modeling and analyzing energy systems [10]. Chang et al. [11], inspired by the work of Connolly et al. [12], analyzed more than 54 energy models in 2021 and concluded that there was no tool capable of modeling the huge number of variables involved in energy transitions. Instead, decision-makers and researchers should select the most appropriate energy tool based on their specific objectives [13]. Two distinct schools of thought have emerged regarding time resolution: one focusing on energy planning and system design at an hourly time resolution, and the other specifically considering electric power systems and utilizing short-term dynamic simulations, typically in seconds and minutes, with a primary focus on frequency stability as a key performance indicator [14].

For the approach with respect to island-centered energy planning and system design at an hourly time resolution, Dorotić et al. [9] reviewed the most relevant scientific contributions to electric vehicle (EV) integration published before 2019 and developed their own

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Nomenclature

PES	Primary energy supply
PV	Photovoltaic
RES	Renewable energy sources
V2G	Vehicle to grid
EV	Electric vehicle
ISIV	Integrated smart island validation
TSO	Transmission system operator

research on vehicle-to-grid (V2G) integration on Korčula Island (Croatia). V2G is a promising technology that enables stationary or parked EVs to function as dispersed reservoirs and to either retain or discharge energy strategically, facilitating the interchange of power between the electrical grid and the EV [15]. The study of Dorotić et al. [9] analyzed its impact on the total import/export of electricity in a 100 % intermittent renewable energy island system. While they acknowledged that their approach could be improved by integrating, for example, multi-objective optimization, they nevertheless concluded that the optimization of different important aspects of the energy system such as storage capacity and the share of V2G would have a significant impact on overall costs and electricity import/export [9].

Among the studies mentioned by Dorotić et al. [9] is an analysis by Pfizer et al. [16] who proposed using electric cars as a means of storing electricity from unstable sources to meet fluctuating demand in a group of islands in Croatia. They achieved this through advanced charging systems that enable V2G connections, allowing for the integration of EVs into the power grid. While this approach was part of a broader energy planning strategy focused on demonstrating that interconnections could increase the share of energy from RES [16], the authors also concluded that V2G allowed for the exploitation of synergies between sectors with the least environmental impact in island systems. However, because this approach did not consider the challenges of isolated islands, the conclusions may not apply to independent islands [9].

A similar analysis was presented in [17], where the authors explored interconnection of the power systems of several of the Canary Islands (Spain). They concluded that 44 % of the transport energy demand could be covered by hydrogen and 53 % by electricity (using smart charging of battery EVs), leaving only 3 % to biofuels [17]. However, the proposal in [17] to install various submarine power transmission lines for an aggregated analysis of the energy systems means that the conclusions that the authors drew are limited to a group of islands with the possibility of interconnection between them, but not in terms of their application to independent islands.

Meschede et al. [18] and Cabrera et al. [19] explored the integration of EVs in two different subtropical islands of the Canary Archipelago. In the first of these [18], the authors examined various fundamental concepts related to achieving a cost optimal 100 % renewable energy system for a subtropical island, taking into account the perspective of the distribution system operator. They considered a scenario in which 80 % of the total vehicles of La Gomera (Spain) are EVs and 50 % of them have the capacity to use smart battery charging at times of surplus electricity generation. Cabrera et al. [19] analyzed different strategies based on the Smart Energy Systems concept [20] to increase the share of RES for the island of Gran Canaria (Spain). Among the different scenarios they analyzed, the authors converted all road transport into electric transport and tested three different strategies for managing the flow between cars and the electricity system: a) without any smart strategy to charge/discharge the EVs; b) considering a smart charging approach; and c) applying the V2G concept. The authors observed that the introduction of EVs (in all strategies used) reduced the primary energy supply (PES) of the energy system. Additionally, the b) and c) strategies improved the flexibility of the energy system.

Child et al. [21] explored electrification of the transport sector in the Åland Islands, arguing that a highly electrified sector could reduce annualized energy system costs and promote employment and international partnerships. They considered both land transport and maritime transport and concluded that the effects of the widespread use of EVs on power systems remain an area of concern.

While all the above studies focused on assessing the overall performance of the energy system, in the particular case of medium-size isolated power systems it is important to not only consider the overall energy system performance but also the effects of simultaneously expanding RES and electrifying a demand sector such as transport on the security and the stability of the power system. It is essential for the system to meet the standards applied by the transmission system operator (TSO). These standards, based on general criteria for the protection of insular and extra-peninsular electrical systems [22], include the definition and limits for each electrical protection and its tripping time.

In this regard, Prina et al. [23] and Pillai et al. [14] argued that more detailed simulations are needed, beyond the scope of energy planning-based approaches, that take into account intra-hour variations, production and consumption dynamics, planning uncertainty, and internal transmission limitations. In this context, Psarros and Papathanassiou [24] recently conducted a literature review on high-RES systems on islands, with a specific focus on generation scheduling from a dynamic and short-term perspective. The review identified a wide range of studies in the area and highlighted the main challenges for both modelling and determining reserve requirements to ensure operational security and stability. The review also noted the computational complexity of the best models, which can result in lengthy execution times. Despite these challenges, the literature suggests that islands can operate satisfactorily with very high levels of RES penetration.

A number of studies, also based on this short-term and dynamic perspective, have been carried out for different islands of the Canary Archipelago to analyze RES penetration and its effects on the power system [25–28]. In [27], a dynamic model of the isolated power system of Gran Canaria was developed to analyze the potential level of RES penetration with or without the installation of a pumped storage system.

In [25], the relationship between stability measurements and the amount of wind power being produced in two small and interconnected islands was analyzed. The maximum allowed duration of a three-phase short circuit before loss of system stability was used as a measurement of stability [25]. Islands tend to have a weakly meshed electricity network and the addition of intermittent power sources can affect the value of different stability parameters. Some authors have proposed the integration of storage technologies such as battery energy storage systems [26] or regulation devices such as flexible AC transmission systems [29] to improve the dynamic behavior on islands or in microgrids.

Pillai et al. [14] highlighted the lack of research bridging the gap between two schools of thought: those that design models for holistic energy system analyses that do not consider dynamic stability, and those that conduct dynamic simulations that are too detailed for general energy system design. They also highlighted the importance, for the validation of planning scenarios, of estimating the gap between results obtained from dynamic operational simulations and those obtained from aggregate computations with a 1-hour resolution. In a gap analysis, they compared the results of the EnergyPLAN model with a dynamic analysis of the power system for future energy scenarios on the island of Bornholm, Denmark. They also discussed the potential of V2G technology to provide ancillary services and support wind power generators in the islanded Bornholm power system. The authors concluded that the EnergyPLAN model can be used to evaluate energy scenarios on an hourly basis, but that the results of the EnergyPLAN model and the dynamic analysis differed significantly. The study also suggested that V2G technology can improve short-term power balancing and provide ancillary services, and that further comparative studies are needed to estimate the fraction of intra-hour operation.

Another study which targeted this gap was carried out by Mendoza-

Vizcaino et al. [30]. These authors proposed a combined energy planning and grid assessment to analyze four different battery technologies. The method they employed was designed to optimize and reduce the backup time of the battery bank and included a grid assessment analysis to obtain a reliable, strong, and safe operation response based on the grid code parameters, even in cases of disturbance. The method was created for small islands and is based on HOMER and Power Factory 15, a module of DIgSILENT GmbH [30,31]. The study [30] noted that investigations into electrification of the transport sector and its integration with energy planning have been conducted, but that the combination of an energy planning approach and an analysis of the power system to validate the feasibility of the proposals was less explored. Interesting studies have also been carried on the development of mathematical models that jointly optimize energy management and trading among microgrids integrated with RES [32,33]. Other studies have integrated EVs as a consumer of the microgrid [34]and used novel control systems [35].

Regarding case studies of larger islands such as Gran Canaria, with a strong dependence on tourism [36], an important energy demand, but also a significant wind and solar energy potential [19], studies have been conducted from either the energy planning perspective [19] or the power system behavior perspective [25–28]. However, no studies have been found in the literature which combine overall energy system analyses from an energy planning approach with more detailed power system analyses, where power balance in every instant is the main item of interest instead of energy balance over a period of time.

Converting all road transport into electric transport and covering this new electric demand with renewable energy can be considered a radical technological change as, according to [1], it involves numerous societal dimensions, including technique, knowledge, organization, products and profits. Therefore, to be able to properly evaluate the validity of such a radical change, an initial analysis stage is required based on an energy planning approach. This stage should not be limited, and it should be able to make a consistent and comparative analysis of all the alternatives, as well as establishing a reference starting point of the system [1]. However, for these alternatives to be considered applicable they need to be validated in a second stage in which the system is analyzed in greater detail, shortening the time scale and assessing any possible stability losses caused by the new technologies introduced. In this context, Prina et al. [23] discussed the use of national-scale models and approaches, which are often employed but may have limitations in cases requiring specific constraints related to spatial and temporal resolution. Such models also rely on simplified representations of electricity system stability, rather than more advanced unit commitment tools [23]. This acquires special relevance in isolated systems in which the balance and stability of the electrical system determine the feasibility of the strategies to be implemented.

The novelty of the present study lies in its presentation of the development of a new method that uses the Smart Energy Systems concept to take advantage of the different synergies between the sectors involved (transport and electricity) and integrates a combined approach focused on two island-centered aspects: energy planning and power system security and stability. We consider this to be critical for isolated energy systems as their weakness and lack of robustness means that new proposals of alternative scenarios need to be as validated as possible. The method is applied to the island of Gran Canaria (Canary Islands, Spain) obtaining results which see important reductions in oil consumption, CO_2 emissions, the total annual costs of the system and the total energy required to supply it. A stability analysis is also performed to determine whether the system can handle a significant electric vehicle load and high renewable energy production without excessive load shedding. As an initial hypothesis, we consider that the need for more renewable energy installations increases with electrification of the transport sector, as energy demand must match energy generation. Hence, if the energy system requires more energy because of the creation of a new demand that comes from electrification of the transport sector, and if that energy comes from renewable energy sources, the generation costs will be lower as renewable energy sources are cheaper than conventional fossil fuel sources. The electricity and transport sectors are firstly modeled to identify an optimal scenario that maximizes RES penetration and electrifies as many vehicles as possible, which is followed by steady state and dynamic analyses of the power system. EnergyPLAN is used to simulate and validate site-specific scenarios from the energy planning approach, while PowerWorld is used to perform steady state and dynamic stability calculations. The aim is not only to solve existing system problems, but also to find an optimal scenario for electrification that considers energy demand and increasing RES contributions. The method evaluates scenarios at critical moments of demand and generation to ensure that the security and stability criteria applied by the TSO are met for the power system.

The second section of this article describes the methods applied, both the general approach and the specific tools used. Section 3 presents and discusses the results, while section 4 details the main conclusions and the implications of using this method.

2. Methods

This section describes the theoretical backgrounds and principles, the tools employed, the approach followed and the procedures which form the basis of the proposed method. The idea is to combine the synergies between the energy system and transport sector electrification with a view to increasing wind and solar photovoltaic (PV) participation in a stand-alone island power system. Firstly, the optimal energy scenario is obtained, which is followed by an analysis of the power system to ensure the security and stability values applied by the TSO are met.

2.1. *Theoretical background and principles*

The method proposed in this article is based on two stages. Firstly, an analysis of the energy system is conducted from an energy planning approach based on the Smart Energy Systems concept [20]. This concept embraces a comprehensive perspective that coordinates the seamless integration of various sectors to discover synergies, aiming for optimal efficiency across the entire energy landscape. In contrast to the narrower focus of the Smart Grid concept, which primarily revolves around electricity, this strategy encompasses the entirety of the energy ecosystem [37]. It delves into the examination of appropriate infrastructure blueprints and operational methodologies to improve the overall energy system [1]. The aim is to properly identify relevant high-RES scenarios exploiting synergies derived from sector integration. Secondly, the high-RES scenarios are analyzed from the power system perspective.

The basic principles which lie behind this new method are as follows:

1. The perspective that is considered involves the energy-transport system sectors of the island, that is to say electricity and vehicles. The model generated for the energy planning phase is based on Smart Energy Systems and global demands and resources, while the optimal design procedure of the entire energy system is implemented to take advantage of possible synergies by combining energy sectors [38]. In this first energy planning phase, the approach considers the entire energy system along with the identification of suitable energy scenario designs and operating strategies [1].
2. A short-term (hourly) perspective of the production of intermittent RES and energy demand is considered to take into account the oscillatory nature of this type of energy source and the potential for making demand more flexible, in this way adapting it to the intermittent nature of RES [19].
3. As a result of the vulnerability of isolated power systems of limited size (islands), a balanced energy system configuration is necessary [19]. Therefore, a technical optimization criterion is used in the planning phase. This is based on equaling and minimizing the sum of

the energy surplus (defined as excess electricity production [38]) and the lack of electricity when meteorological conditions are insufficient to meet demand with RES.

4. In the transport sector it is assumed that all the EVs will be charged in certain predefined hours [39]. Each scenario will be studied with different EV charging time frames, which means that in certain moments of the day there will be an important increase in electricity demand.
5. The overall method searches for a balanced and RES-optimal energy system, but also an electrically validated energy system configuration. Therefore, after obtaining an optimal energy planning solution, the stability and voltage conditions are calculated and checked for the system. As security of the supply is one of the most important criteria that electrical power systems must meet, this impacts the viable RES configurations.

2.2. *The EnergyPLAN simulation tool*

The wide variety of tools available in the market includes diverse models whose principal objective is to analyze the influence of RES in energy systems [11,40]. For this research, the EnergyPLAN software was selected as it is one of the five recommended tools [12] for the energy planning approaches described in section 1 and is a popular choice for academic studies, with 315 journal articles identified in the energy systems literature as of July 2022 [4].

EnergyPLAN is a particularly suitable tool for this study because it allows the deterministic modelling of an energy system and performs hourly simulations with a time frame of one year. In addition, it was specially designed for application of the Smart Energy Systems concept and is able to simulate the entire energy system, interrelating the different sectors. In this research, EnergyPLAN can simulate synergies across the transport and energy sectors, optimizing both. EnergyPLAN can simulate the electricity consumption of vehicles as a flexible demand, thus accommodating a higher share of RES.

An important quality of EnergyPLAN is its short computational time, with the software able to simulate and model each new scenario rapidly. As the procedure presented in this study requires a high number of calculations and simulations to find optimal scenarios, computational time is important in this research.

2.3. *The MATLAB Toolbox for EnergyPLAN*

One of the limitations of EnergyPLAN is that it only allows for a restricted number of subsequent executions with a limited number of decision variables in each execution [13]. The software's manual mode, which combines optimization of both the operational and planning phases, has been previously highlighted by researchers [41–43]. To maximize the potential of EnergyPLAN, some authors have recommended combining it with other computational tools [42–44].

The MATLAB Toolbox for EnergyPLAN provides high-level technical computing capabilities within the MATLAB environment to enhance the potential of the EnergyPLAN model in energy planning [13]. This toolbox plays an essential role in the present study by enabling the automated generation of various scenarios from MATLAB. As a result, the MATLAB Toolbox can be used to create scenario files, execute EnergyPLAN and collect results, making it useful for analyzing a large number of outcomes.

2.4. *PowerWorld*

Of the various software tools that can be used to analyze a power system and assess its security and stability, PowerWorld was selected for the present study. The educational version of the tool allows the handling of a maximum of 41 nodes or buses [45], enabling the analysis of power systems in some of the largest islands globally. PowerWorld is a simulation tool designed for high-voltage electrical power systems and can run dynamic simulations in the order of about a minute long after an event [46].

In the method that has been developed, it is proposed to analyze the power system performance, in terms of losses, power, frequency stability and voltage, of the optimal scenario obtained from the EnergyPLAN analyses. With this tool, it is possible to confirm that the scenario obtained after successive simulations of EnergyPLAN and MATLAB meets the network quality criteria that are necessary for this type of system.

The program can compute the most important electrical variables of the system and its components to assess security in a given scenario, such as network voltages and power flows through transmission lines, using the classic full Newton-Raphson method [47]. PowerWorld can also provide electrical variables to assess the power system stability in a new scenario, such as the speed and power output of generating units and the system frequency after different types of events have been applied.

To use the program, an electrical system configuration has to be introduced, including the characteristics of the buses representing the network, the generating units, the transmission lines, the power transformers and the loads. Previous island-focused PowerWorld uses in the scientific literature support its application in the method proposed in the present paper. In [45], PowerWorld was utilized with the objective of creating publicly accessible power system models for prominent islands located in the Philippines using publicly available data. Mendes et al. [46] highlighted the utility of PowerWorld and used it to evaluate the electricity system of Maio, a Cape Verde island, considering various factors such as the island's RES potential, technical specifications of the electricity system, and financial constraints.

2.5. *Multi-objective optimization model*

A multi-objective optimization model is applied to calculate a set of acceptable possible optimal solutions, called a Pareto front [48]. These solutions are obtained on the basis of all the different conflicting objectives chosen for the evaluated transport-energy system [49]. This resulting Pareto front allows decision makers a better understanding of the overall system, enabling them to explore all the consequences of a decision with respect to the various conflicting objectives [49,50].

According to [51–53], a multi-objective problem can generally be formulated as follows:

$$\text{minimize : } \boldsymbol{y} = \boldsymbol{f}(\boldsymbol{x}) = (f_1(\boldsymbol{x}),\ f_2(\boldsymbol{x}), \cdots, f_k(\boldsymbol{x})) \tag{1}$$

$$\text{subject to:} \boldsymbol{g}(\boldsymbol{x}) = (g_1(\boldsymbol{x}), g_2(\boldsymbol{x}), \cdots, g_m(\boldsymbol{x})) \leq 0$$

$$\boldsymbol{h}(\boldsymbol{x}) = \left(h_1(\boldsymbol{x}), h_2(\boldsymbol{x}), \cdots, h_p(\boldsymbol{x})\right) = 0$$

$$l_i \leq x_i \leq u_i, i = 1, 2, \cdots, n$$

$$\text{where:} \boldsymbol{x} = (x_1, x_2, \cdots, x_n) \in \boldsymbol{X}$$

$$\boldsymbol{y} = (y_1, y_2, \cdots, y_k) \in \boldsymbol{Y}$$

$\boldsymbol{x}$ is the vector of n decision variables (parameters) and $\boldsymbol{y}$ is the vector of k objective functions. $\boldsymbol{X}$ is the decision space and $\boldsymbol{Y}$ the objective space. $\boldsymbol{g}(\boldsymbol{x})$ is a set of m inequality constraints with feasible solutions $(\boldsymbol{e}(\boldsymbol{x}) \leq 0)$, and $\boldsymbol{h}(\boldsymbol{x})$ represents a set of p equality constraints. l_i and u_i are used to represent the lower and upper limits of the i-th variable, respectively.

If a candidate solution $\boldsymbol{x} \in \boldsymbol{X}$ satisfies the constraints in Eq. (1), then $\boldsymbol{x}$ is called a feasible solution. All feasible solutions conform the feasible solution set.

Formally, it is said that a feasible solution $\boldsymbol{x}$ Pareto dominates another feasible solution $\boldsymbol{x}'$ if and only if:

$$\begin{cases} f_i(\boldsymbol{x}) \leq f_i(\boldsymbol{x}'), \forall i \in \{1, 2, \cdots, m\} \\ f_i(\boldsymbol{x}) < f_i(\boldsymbol{x}'), \exists i \in \{1, 2, \cdots, m\} \end{cases} \tag{2}$$

Therefore, $\boldsymbol{x}$ is called a Pareto optimal solution, or Pareto nondominated solution, if and only if it is not dominated by any other feasible solution. This means that solution x cannot be improved in one of the objectives without adversely affecting another objective [50]. The analytical expression of the Pareto front cannot usually be obtained in practical problems [50,53].

The particular application of the optimization model to the transport-energy systems for the electric vehicle integration on islands can be represented as follows:

$$\text{minimize: } y_1 = totalannualCO_2emissions(Mt),$$

$$y_2 = 100\% - RESshareofPES(\%)$$

$$y_3 = totalannualfuelconsumption, PES, (TWh)$$

$$y_4 = totalannualoilcontributiontoPES(TWh)$$

$$y_5 = maximumrequiredhourlyimport(MW)$$

$$y_6 = imports/exportsintersectionpoint(TWh)$$

$$y_7 = annualvariablecosts(M€)$$

$$y_8 = totalannualcosts(M€) \tag{3}$$

$$\text{subject to:} Currentannualelectricvehicledemand \le x_1 \le maximumfeasiblevalue,$$

$$Currentelectricvehiclepowerconsumption \le x_2 \le maximumfeasiblevalue$$

$$Currentwindpower \le x_3 \le windpowertocover100\%electr.demand$$

$$CurrentPVpower \le x_4 \le PVtocover100\%electricitydemand,$$

$$\text{where:} x_1 = annualelectricvehicledemand(MWh/y),$$

$$x_2 = hourlyelectricvehiclepowerconsumption(MW),$$

$$x_3 = windpowerinstalledcapacity(MW)$$

$$x_4 = PVpowerinstalledcapacity(MW)$$

This problem is generally formulated by 4 decision variables (annual electric vehicle demand, electric vehicle power consumption, wind power capacity installed in the energy system and PV power capacity) and 8 potential objective functions. However, the number of potential objective functions can be increased or reduced depending on data availability or the aims of the decision makers. The potential objective functions are the annual CO_2 emissions, the RES share of PES, the total annual fuel consumption (PES), the total annual oil contribution to PES, the maximum required hourly import, the intersection point of imports and exports for each water infrastructure (which defines the energy storage size required to minimize fossil fuel consumption), the annual variable costs, and the total annual costs. All of these objective functions are calculated by the EnergyPLAN software. Their mathematical model and detailed descriptions can be found in [54,55].

2.6. *Case study: The island of Gran Canaria*

The case study, which follows the procedure described in this research, considers Gran Canaria, a Spanish island located in the Canary Archipelago in the Atlantic Ocean (Fig. 1). At the start of 2019, Gran Canaria had a population of 852,688 inhabitants [56].

2.7. *Integrated smart island validation procedure*

The different parts of the integrated smart island validation (ISIV) procedure used in this study are shown in Fig. 2. The ISIV procedure can be applied to any electricity system in the world if it meets the criteria of isolated small-sized systems, like those used in islands.

2.7.1. *Step 1. Identification of the energy resources and transport demands*

In Step 1, the researcher identifies the transport sector electricity demand, other electricity demands, and the energy sources. For the analysis in this article, all the data collected in this step come from official reports and statistics published by local institutions and governments [56,58]. In addition to up-to-date data, it is important to map the potential viable growth of the different resources that are available, the potential installation and use of new RES, any particular features of the target island that could benefit or limit the future exploitation of RES, and any existing medium- or long-term energy plans.

In this step, a simplified representation of the energy resources and demands of Gran Canaria and its transport sector were mapped, considering only passenger cars. In addition, the particular characteristics of the island were outlined along with the energy-transport sector plans and regulations.

The current energy system of Gran Canaria is predominantly based on oil, with a wind-dominated renewable energy of just below 0.51 TWh in 2019 (Fig. 3). In the same year, the total generation capacity of the island was 1220.06 MW, of which 1024.06 MW came from conventional sources [47].

2.7.1.1. Electricity demand in Gran Canaria. In 2019, the peak electricity load in Gran Canaria occurred in October, and was around 523

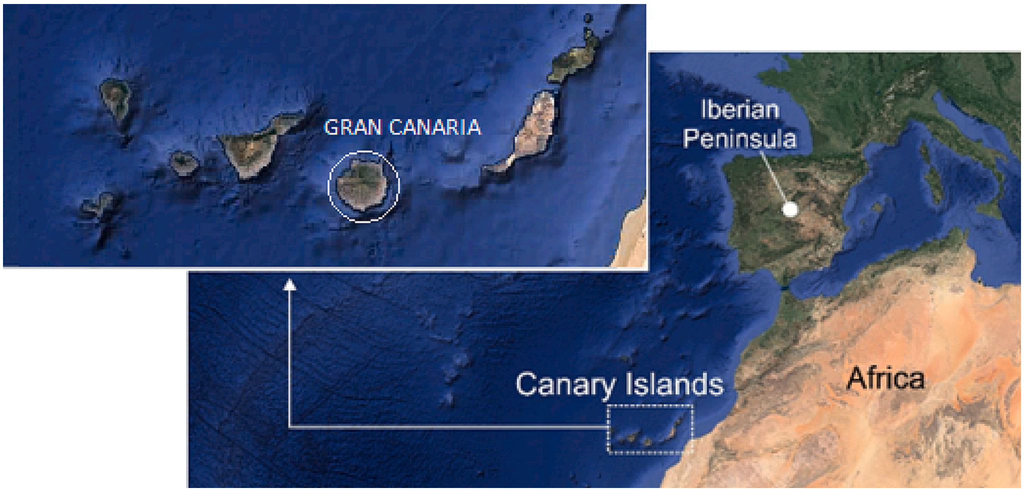

Fig. 1. Geographical location of the island of Gran Canaria [57].

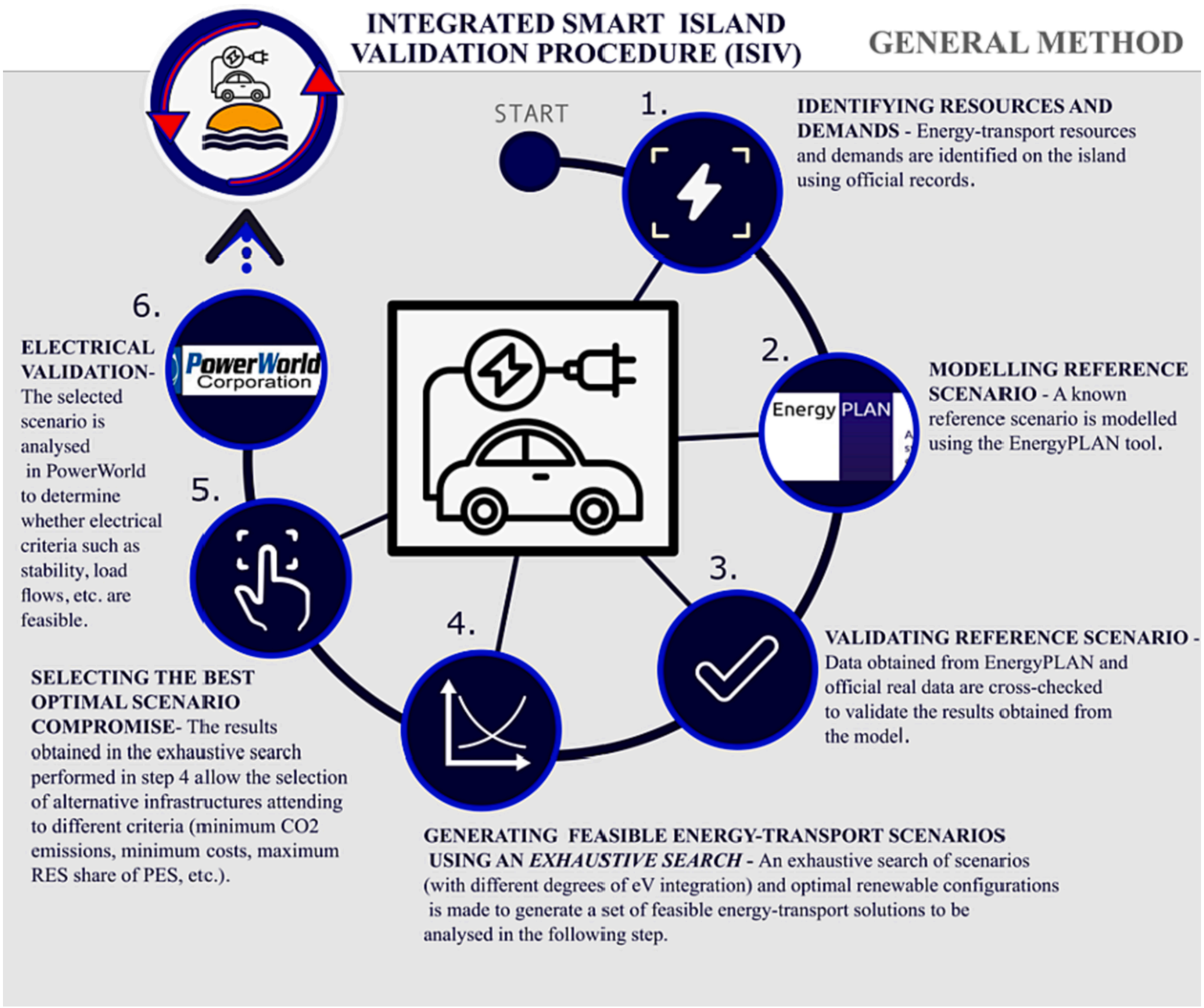

Fig. 2. Graphical representation of the steps employed in the general ISIV method.

MW. The minimum load of just below 262 MW occurred in January (Fig. 4). The power demand is strongly affected by tourism seasonality. The October peak was a consequence of the beginning of the high season combined with hot days, and hence elevated demand for air conditioning.

2.7.1.2. Wind and PV resources in Gran Canaria. Although there are high PV and wind energy resources in Gran Canaria (see Fig. 5a and Fig. 6a, respectively), their exploitation is currently limited principally because of the penetration problems associated to renewable energy in isolated electric power systems. In 2019, Gran Canaria had an installed PV capacity of 37.17 MW and an installed wind power capacity of 159.30 MW [59]. The highest hourly PV production in 2019 was 28.22 MW (Fig. 5c), and the mean maximum hourly production of 20.75 MW was at 13:00–14:00 h (Fig. 5b).

Given its high wind resource (Fig. 6a), Gran Canaria has a large number of installed windfarms, with peak production of 140.2 MW in 2019 occurring at the end of July (Fig. 6c) when the trade winds that traverse the islands are at their strongest. Maximum hourly wind energy production averaged 71.8 MW and happened around 20:00 h, while the corresponding mean minimum value was 46.5 MW at around 08:00 h (Fig. 6b).

The wind and PV power installations on the island were installed by different promoters with the aim of decarbonizing the energy sector.

2.7.1.3. Transport sector in Gran Canaria. The Sankey diagram of Fig. 3 shows the demand of the transport and energy sectors considered in this study for the analysis of the application of the method. Only passenger cars are considered. Most of the consumption for this type of vehicle is oil-based. The percentage of electricity-based mobility is insignificant [59].

As can be seen in Fig. 3, most of the fossil fuels are consumed in the electricity sector, with the transport sector in second position. Electrifying transport and increasing the generation of renewable energy aims to improve the system by attacking it from two different fronts.

2.7.2. Step 2. Reference scenario set-up and modelling

In the second step, EnergyPLAN is used to model a reference system of the target electricity system. This is typically based on the most recent year with full statistical data available. Temporal distributions of demand and renewable energy production are required in this step, in addition to aggregated demands and other production system characteristics.

To assess the energy system costs, data from the Danish Energy Agency [62], the Spanish Institute for Diversification and Energy Saving [63], and other local organizations [36,59,64] were used. The costs presented in Table 1 are shown without any applied discounts and are those that are the most important with specific reference to the present study. Fixed operating and maintenance (O&M) costs are given as a percentage of the investment costs.

Fuel costs with a significant weight in the system are shown in Table 2.

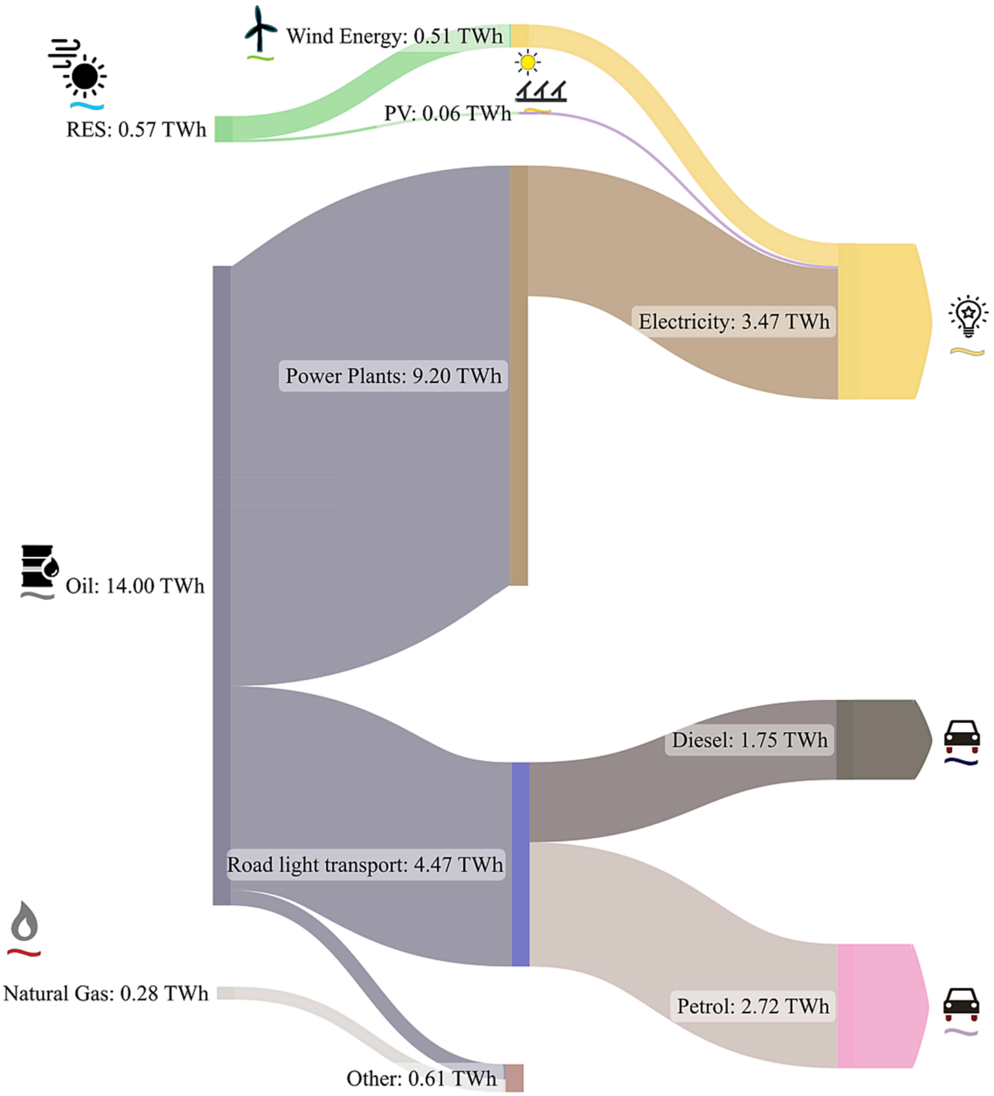

Fig. 3. Sankey diagram of a simplified energy system of Gran Canaria in 2019 (TWh). Data sources: [56,59].

In addition, a price of 24.92 EUR/t CO_2 is considered based on historical EU data [67].

2.7.3. Step 3. Reference scenario validation

Once the reference scenario is implemented, it is validated by cross-checking the results obtained from the EnergyPLAN simulation against the known real/measured data. Deviations between the model result and real data can be quantified and, if acceptable, the model is considered validated.

Steps 2 and 3 can be iterated to refine the model parameters for accurate representation of the reference system.

After identifying the energy system and modelling the reference scenario in EnergyPLAN, the simulation was validated. Tables 3-6 present quantitative results for comparison between the 2019 statistical data and the data generated through the EnergyPLAN simulation. Table 3 represents the monthly energy electricity demand of the actual data gathered from official reports and those generated by EnergyPLAN. Table 4 shows the monthly peak electricity powers supplied. The difference in the amount of electricity generated by the various production types between the actual data and the simulations are shown in Table 5. Table 6 shows the differences between the actual data and the EnergyPLAN simulation data for annual fuel consumption by energy source. In articles related to engineering, error values below 5 % in simulations are acceptable. The demand is an input to the model and for this reason such low errors are obtained.

The maximum variation in monthly electricity energy demand between the simulated data and the real data occurred in December at just 0.005 %.

The difference between the modelled and actual monthly peaks of electrical power is shown in Table 4. The maximum difference is found in May, but at 0.35 MW the difference is just 0.072 %.

After analyzing the differences between the reference model and the actual 2019 Gran Canaria data, the accuracy of the model was accepted as the largest variation was just −1.67 %.

2.7.4. Step 4. Generation of different energy-transport scenarios and optimization

The fourth step is the most complex part of the method and is supported by the MATLAB Toolbox for EnergyPLAN. Here, an iterative and layered approach is developed with the objective of finding the optimal RES design for each new alternative transport configuration. As can be seen in Fig. 7, the MATLAB Toolbox for EnergyPLAN uses the validated EnergyPLAN reference scenario. The parameters that define this scenario are split into two categories: unaltered variables (constants) and alterable variables. The alterable variables are modified with each iteration with the objective of maximizing RES integration in the energy

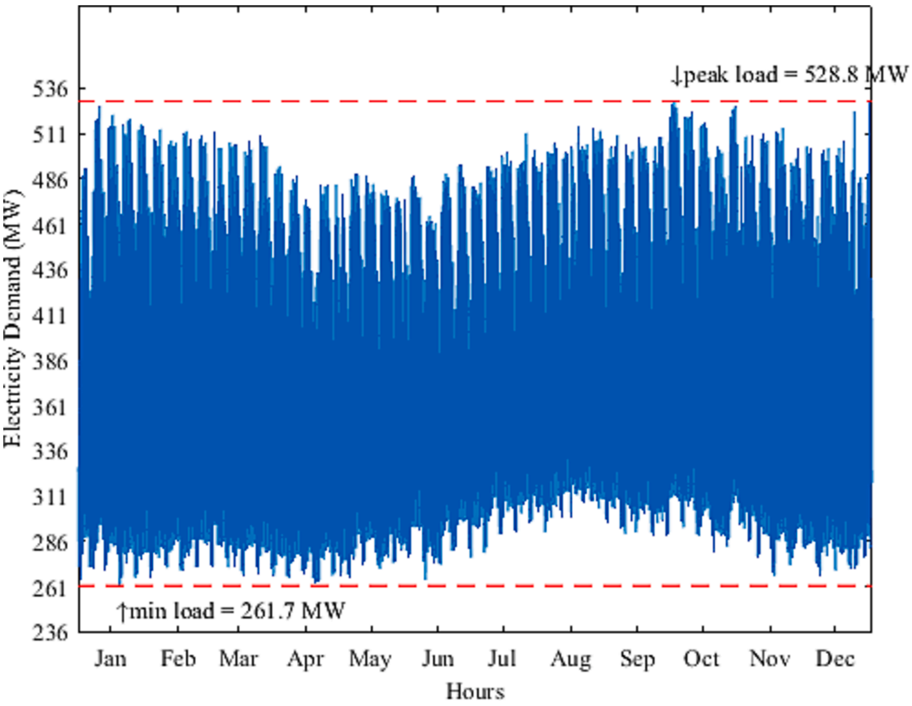

Fig. 4. Hourly average electricity demand in Gran Canaria in 2019 [60].

system.

The MATLAB program was used for this step of the procedure. The objective of this program is to modify the alterable variables (annual EV demand, hourly EV power consumption, wind power capacity and PV power capacity) within certain constraints. For this study, the optimization model is specifically formulated as follows:

minimize: $y_1 = totalannualCO_2emissions(Mt)$,

$$y_2 = 100\% - RESshareofPES(\%)$$

$$y_3 = totalannualfuelconsumption, PES, (TWh)$$

$$y_4 = totalannualoilcontributiontoPES(TWh)$$

$$y_5 = maximumrequiredhourlyimport(MW)$$

$$y_6 = imports/exportsintersectionpoint(TWh)$$

$$y_7 = annualvariablecosts(M€)$$

$$y_8 = totalannualcosts(M€) \tag{4}$$

subject to: $18.2MWh \le x_1 \le 1.82GWh$

$$0 \le x_2 \le 552MW$$

$$159.3MW \le x_3 \le 839MW$$

$$37.17MW \le x_4 \le 1476MW$$

where: $x_1 = annualelectricvehicledemand(MWh/y)$,

$$x_2 = hourlyelectricvehiclepowerconsumption(MW),$$

$$x_3 = windpowerinstalledcapacity(MW)$$

$$x_4 = PVpowerinstalledcapacity(MW)$$

The electricity demand of EVs was varied in steps of 10 %, from the extrapolated 2019 demand of 18.2 MWh to 100 times this value (1.82 GWh). A total of 5808 scenarios were simulated. Twelve (12) electrification penetrations of the transportation sector were studied for four (4) different charging time frames (for further details, see section 4.2.1 of [19] or section 3.4 and Fig. 4 of [48]). The 12 scenarios of EV penetration in the system comprised an initial scenario of 0 %, a second of 5 %, a third of 10 %, followed by further 10 % increases up to 100 %. These twelve scenarios were subsequently studied with different charging time frames.

In this study, four types of EV charging time frames were studied and in each simulation the EV could only be charged in certain hours (Fig. 8). The four load schedules studied were evaluated based on what can be assumed to be optimal for the electrical system. In the C1 scenario charging takes place during night hours when the population is less active. In the C2 scenario charging takes place when there should be more renewable energy production, in the central hours of the day. In the C3 scenario charging is possible all day and night, distributing the electrical demand. Finally, in the C4 scenario charging of vehicles is possible at night and in daytime hours when overall demand is less and the price should be lower.

The general procedure was used to find the minimum intersection point between imports (i.e., conventional fossil fuel energy needs) and exports (i.e., excess renewable electricity production in each power system scenario when EV electric demand increases). The intersection point approach (equalizing imports and exports) was chosen because it is assumed that, if that energy could be stored, it would be the optimal point where the energy demand of the system would intersect with the necessary associated production. The intersection point is required to enable determination of the energy storage size required to minimize fossil fuel consumption. For each transport scenario, an analysis was also performed to find the best wind:PV power capacity ratio using the MATLAB Toolbox for EnergyPLAN [13].

2.7.5. Step 5. Selection of the most appropriate energy-transport scenario

The decision variables are registered for each optimal design and so, in this step, multi-objective criteria are applied. With the contribution of all the variables, a configuration is generated based on a trade-off between the following aspects: CO_2 emissions, RES share of the PES, total annual PES, total annual oil contribution to PES, maximum power

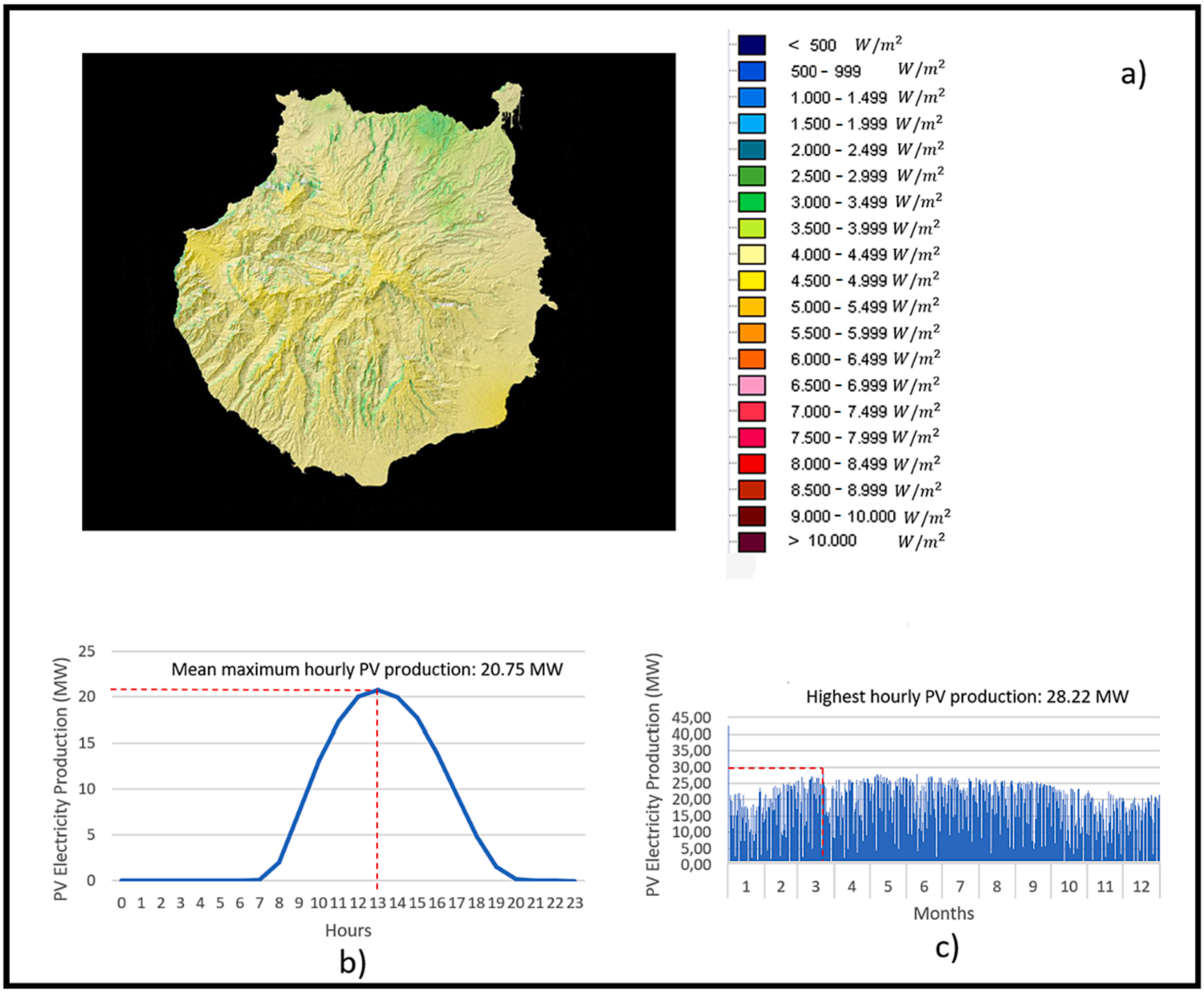

Fig. 5. Photovoltaic energy resource in Gran Canaria. (a) Average global irradiation map for the island of Gran Canaria; (b) Mean maximum hourly PV production in Gran Canaria, 2019; (c) Daily pattern of mean hourly PV electrical power production in Gran Canaria, 2019. Source of maps: [61]; Source of electrical power production data: [60].

necessary from conventional sources (maximum import), import/export intersection value, variable costs, and total annual costs (Fig. 7).

2.7.6. Step 6. Electrical validation

Once the final reference scenario in terms of energy has been selected, it is translated to PowerWorld, where replication can be performed of how the different types of generating units and loads work.

2.7.6.1. Modelling the optimal electrical scenario in PowerWorld. Essentially, the analysis of the electrical power system aims, firstly, to ensure that the system is in a secure state of operation at any given moment in normal operation. For this, the power balance between generated power and load plus transmission losses must be satisfied, at the same time as network voltages remain within a predetermined security range and both generators and transmission lines and other elements maintain sufficient reserve margins to ensure the system is in a secure state of operation. Secondly, the analysis aims to assess whether in the event of an unexpected power imbalance the system can continue to operate in a stable manner.

Before the incorporation of future new renewable generation facilities, Spanish regulation seeks to ensure the security and stability of the power system by determining the maximum capacity of the system to accommodate new power injections into the network. As an example of the concepts involved, we can consider the definition of the access capacity as the maximum active power that can be injected in the network. Access capacity is determined by the TSO for all the transmission network nodes and a new renewable facility can be incorporated into the system only if there is sufficient access capacity [68].

After simulation of the optimal EnergyPLAN scenario in PowerWorld, this research considers whether the aforementioned criteria are met.

2.7.6.2. Analysis of the electrical power system in the optimal scenario. To determine the access capacity, an assessment is made of the robustness of the system to maintain network voltages within established operating margins against variations of renewable power in normal operation. The maximum injectable power in the nodes that does not cause overloads in the branches of the transmission network is also determined, always with the voltages within the permitted limits.

The set of protection coordination criteria and methodologies applied by the TSO also establishes aspects that must be met to maintain the critical clearing time (CCT) at optimal values. The CCT is the maximum time during which a disturbance can be applied without the system losing its stability and is one of the most common criteria for evaluation of the transient stability of a power system. Therefore, the optimal EnergyPLAN scenario is also studied using several cases of a

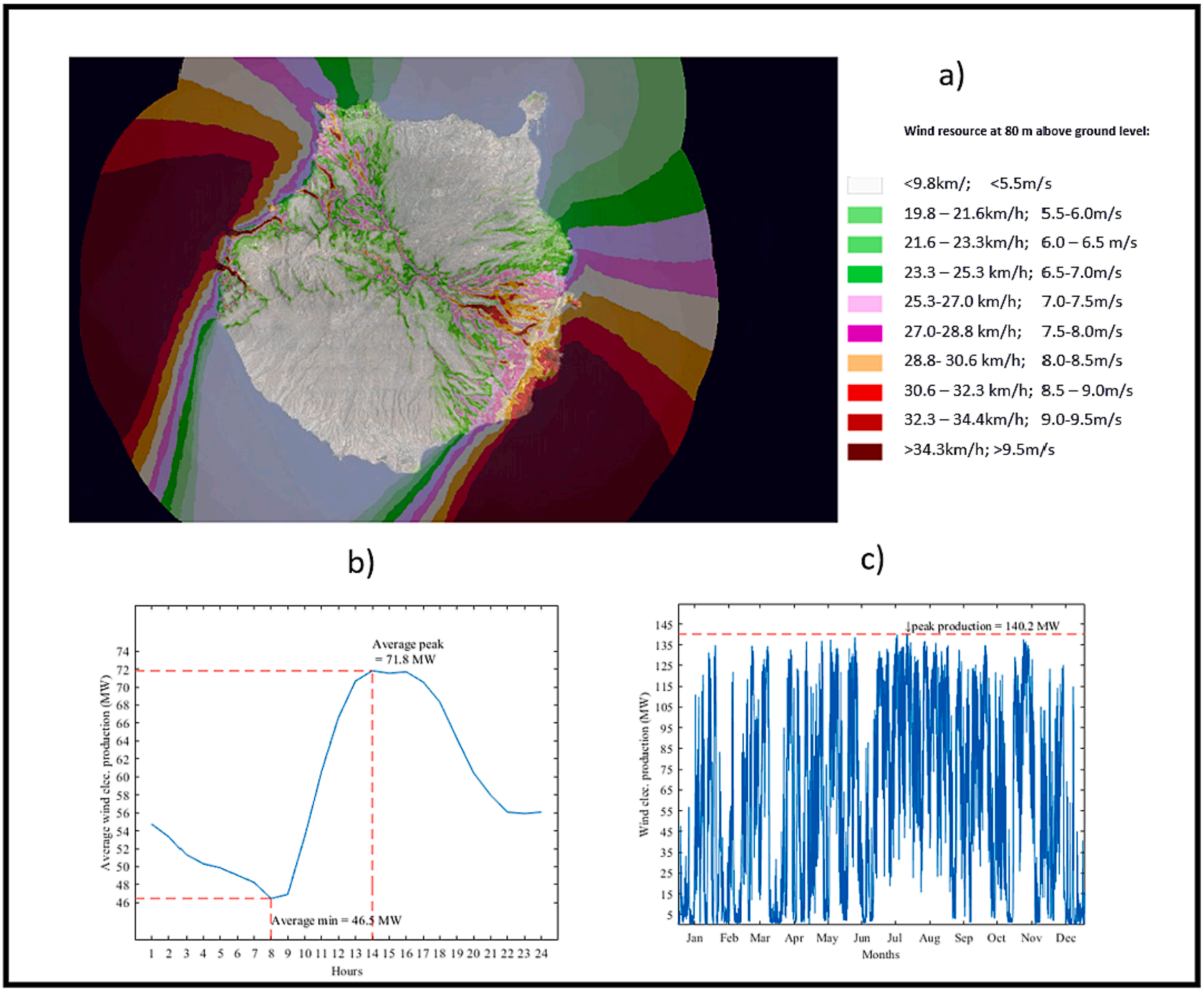

Fig. 6. Wind energy resource in Gran Canaria. (a) Average wind speed map for the island of Gran Canaria; (b) Daily profile of mean hourly wind power production in Gran Canaria, 2019; (c) Mean hourly wind electricity production in Gran Canaria, 2019. Source of maps: [61]; Source of electrical power production data: [61].

Table 1
Costs of installations and vehicles for the case study of Gran Canaria. Sources: [59,63,65,66].

Installations/cars	Investment cost	Fixed O&M (%)	Lifetime (years)
Power plants	0.99 M EUR/MW-e	3.05	20
Wind power	1.2 M EUR/MW-e	2.97	20
Photovoltaic	0.5 M EUR/MW-e	0.60	20
Electric vehicles	18.06 M EUR/unit	6.99	15
Conventional vehicles	20.56 M EUR/unit	4.09	20

Table 2
Fuel costs for the Gran Canaria case study. .

Fuel	Price (EUR/GJ)
Diesel	15
Fuel oil	11.9
Natural gas	9.1

Source: [54]

Table 3
Monthly electricity demand obtained from the EnergyPLAN simulation and actual values for the year 2019 in Gran Canaria [58].

Month	Actual 2019 (TWh)	EnergyPLAN 2019(TWh)	Difference (%)
January	293.48	293.47	−0.003 %
February	265.04	265.04	−0.001 %
March	290.14	290.13	−0.004 %
April	273.66	273.66	0.000 %
May	285.06	285.06	−0.003 %
June	277.91	277.91	0.001 %
July	299.48	299.48	−0.002 %
August	304.96	304.96	−0.003 %
September	292.44	292.44	0.000 %
October	306.49	306.49	−0.003 %
November	289.14	289.13	−0.004 %
December	292.97	292.96	−0.005 %
Total	3 470.78	3 470.70	−0.030 %

three-phase short circuit event to demonstrate that the system maintains stability and that load shedding is between the limits established by the TSO. A three-phase short circuit is generally considered the most severe disturbance in a power system. In the beginning of the short circuit the

Table 4
Monthly peak electrical power demand obtained from the EnergyPLAN simulation and actual values for the year 2019 in Gran Canaria [58].

Month	Actual 2019 (MW)	EnergyPLAN 2019 (MW)	Difference (%)
January	525.78	526.00	0.041 %
February	513.27	513.00	−0.052 %
March	512.07	512.00	−0.013 %
April	493.17	493.00	−0.034 %
May	488.65	489.00	0.072 %
June	493.28	493.00	−0.057 %
July	511.25	511.00	−0.049 %
August	514.97	515.00	0.006 %
September	519.12	519.00	−0.022 %
October	528.82	529.00	0.035 %
November	514.17	514.00	−0.032 %
December	527.65	528.00	0.066 %
Peak electrical power (MW):	511.85	511.83	−0.040 %

Table 5
Electricity production in Gran Canaria in 2019 obtained from the EnergyPLAN simulation and actual values for the year [58].

Production type	2019 Production (GWh)	EnergyPLAN 2019 (GWh)	Difference (%)
Power plants	2 910.3	2 910	−0.01 %
Wind	514.7	515	0.06 %
PV	54.2	54	−0.35 %

Table 6
Fuel consumption in Gran Canaria in 2019 and the EnergyPLAN simulation for this data [58].

Fuel	2019 Fuel consumption (GWh)	EnergyPLAN Fuel consumption 2019 (GWh)	Difference (%)
Oil	14238.1	14,000	−1.67 %
Natural gas	278	280	0,71 %
Renewable	569.9	569	−0.16 %

speed of the synchronous generator will increase because the short circuit implies low network voltages and therefore low power is seen by the electrical generators, as can be observed in Eq. (5):

$$\overline{S} = P_e + jQ_e = \overline{V} \bullet \overline{I}^* \tag{5}$$

where $\overline{S}$ is apparent power, P_e is electrical power, Q_e is reactive power, $\overline{V}$ is voltage, and $\overline{I}^*$ is intensity.

In the case of a short circuit in terminals of a synchronous generator, $V = 0$ and, as is represented in Eq. (6), the electrical power drops to 0 as well:

$$P_e = Real(\overline{V} \bullet \overline{I}^*) = 0 \tag{6}$$

When a short circuit occurs in a different network node, the terminal voltage of the running synchronous generators drops to a low value, and so P_e also has a low value. Consequently, because of the relations defined in Eq. (7), the speed of the synchronous generators will increase as there is a significant imbalance between mechanical and electrical power:

$$\frac{d\omega}{dt} = \frac{\pi \bullet f}{H} \bullet (P_m - P_e) \tag{7}$$

where ω is angular velocity, f is the rated frequency (50 Hz in Europe), H is the inertia constant (kinetic energy stored in the rotation of the generator divided by the rated power of the generator) and P_m is mechanical power. So, the network frequency also increases proportionally to the speed of the synchronous generators, eventually causing activation of over frequency protection in some cases. The generator can also disconnect for its self-protection just after the short circuit is cleared.

Once the short circuit is cleared, network voltages and consequently the loads are recovered, and the generators will decrease their speed. If the frequency decreases to a certain value that could be a risk for the stability of the power system, some of the load is shed. Therefore, the conventional generators will gain speed and the voltage and frequency will rise, with the goal of reaching a new steady state acceptable to the TSO.

The present research is centered on the electrical systems of isolated territories, with current Spanish regulations defining a disturbance as critical in the following cases:

- CCT less than 100 ms.
- Loss of synchronism between coherent generation areas
- The final steady state of the system does not meet the security criteria and system operation for steady state.
- Losses of more than 10 % of the demand due to the direct action of load shedding produced by frequency variations.
- Damping of more than 5 % in the electrical power oscillations of some generator.

In this research, the loss of more than 10 % of demand due to the direct action of the load shedding mechanism due to frequency variations will be the main focus for assessment of the feasibility of the optimal EnergyPLAN scenarios. This approach was chosen because it is usually the main determining factor in insular systems [25].

3. Results and discussion

Table 7 shows a sample of the results obtained and, more specifically, the following data gathered from the EnergyPLAN output files:

- Curve of EV power consumption.
- Percentage of EVs integrated in the energy system (%).
- Percentage of fuel-based vehicles integrated in the energy system (reverse of the previous variable) (%).
- PV power capacity required (MW) and in percentage (%) of total electricity demand.
- Wind power capacity required (MW) and in percentage (%) of total electricity demand.
- Total annual CO2 emissions (Mt).
- RES share of PES (%).
- Total annual PES (TWh).
- Total annual oil contribution to PES (TWh).
- Import/export intersection value, in TWh and in percentage (%) of total electricity demand.
- Total annual costs of the energy system, in M€.

All the optimal feasible solutions shown in Table 7 are also represented in different charts in Fig. 9 using only two potentially conflicting target variables in each. More specifically, Fig. 9a shows the results of the optimal solutions in terms of total annual costs (M€) vs. percentage of fuel-based transport integrated in the system (%), Fig. 9b represents the obtained solutions in terms of total annual CO_2 emissions (Mt) vs. percentage of fuel-based transport integrated in the system (%), Fig. 9c represents the obtained solutions in terms of total annual fuel consumption, PES, (TWh) vs. percentage of fuel-based transport integrated in the system (%), Fig. 9d represents the obtained solutions in terms of total annual oil consumption (TWh) vs. percentage of fuel-based transport integrated in the system (%) and Fig. 9e shows total annual costs for the solutions vs. import/export intersection values (TWh), which are equivalent to the annual energy storage needs to avoid fossil fuels in the system. In Fig. 9, the Pareto fronts are represented by discontinuous lines.

Shown in red in Fig. 9 and Table 7 is the optimal energy-transport solution obtained after applying the proposed method to the island of

Fig. 7. Software framework and optimal search procedure executed in step 4 of the ISIV method.

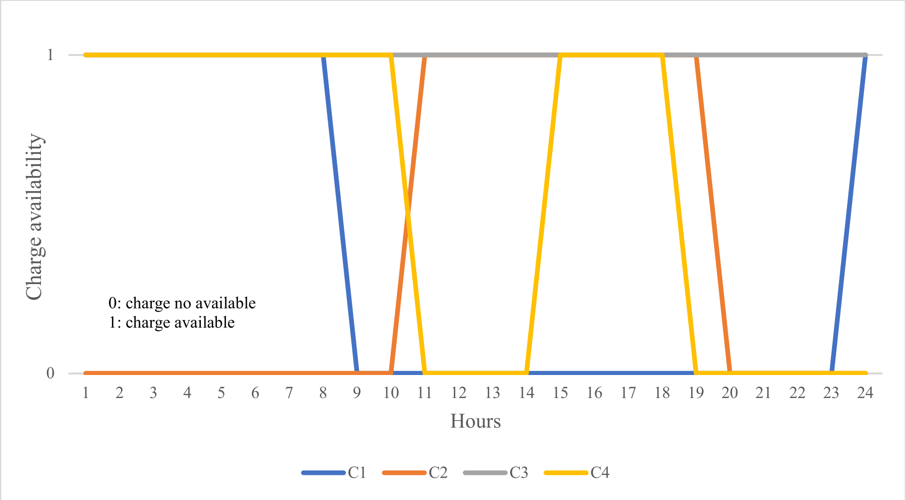

Fig. 8. Types of electric vehicle charging time frames. Blue line: C1 charging time frame (24:00–08:00). Orange line: C2 charging time frame (13:00–19:00). Grey line: C3 charging time frame (all day and night). Yellow line: C4 charging time frame (24:00–08:00 and 15:00–18:00). The number 1 corresponds to available charging and 0 to unavailable charging.

Table 7
Representative sample of the total set of optimal feasible smart energy-transport solutions obtained after applying the proposed method on the island of Gran Canaria.

EV power consumption curve	Electric-based vehicles	Fuel-based vechicles	PV power		Wind power		CO_2	RES of PES	Total annual PES	Total annual oil	Import/Export		Total annual costs
		%	MW	%	MW	%	Mt	%	TWh	TWh	TWh	%	M€
-*	**0**	**100**	**37.2**	**2.5**	**159.3**	**17.13**	**3.79**	**3.8**	**14.84**	**14.00**	**2.91**	**83.62**	**950**
C1	0.00	100.00	302	20	799.50	85.97	3.046	20.8	14.52	11.22	2.0358	58.50	892
C1	5.00	95.00	311	20	819.36	85.89	3.013	21.4	14.48	11.10	2.0671	57.90	884
C1	10.00	90.00	321	20	838.30	85.63	2.982	22.0	14.44	10.98	2.1011	57.41	876
C1	20.00	80.00	340	20	877.08	85.49	2.927	23.1	14.38	10.77	2.1766	56.68	862
C1	30.00	70.00	180	10	1000.57	92.65	2.906	24.1	14.46	10.70	2.2935	56.91	857
C1	40.00	60.00	189	10	1044.13	92.48	2.861	25.2	14.44	10.53	2.3811	56.56	846
C1	50.00	50.00	199	10	1086.97	92.27	2.820	26.2	14.44	10.37	2.4746	56.37	834
C1	60.00	40.00	208	10	1130.38	92.28	2.784	27.3	14.46	10.24	2.5726	56.29	824
C1	70.00	30.00	217	10	1173.49	91.97	2.750	28.3	14.48	10.11	2.6742	56.30	814
C1	80.00	20.00	227	10	1324.22	99.94	2.679	31.2	14.71	9.84	2.7312	55.40	844
C1	90.00	10.00	237	10	1371.50	99.75	2.647	32.2	14.76	9.72	2.8346	55.36	801
C1	100.00	0.00	246	10	1419.27	99.60	2.616	33.3	14.81	9.61	2.9403	55.48	793
C2	0.00	100.00	302	20	799.50	85.97	3.046	20.8	14.52	11.22	2.0358	58.50	892
C2	5.00	95.00	467	30	745.99	78.20	2.980	21.6	14.35	10.97	2.0273	56.79	874
C2	10.00	90.00	482	30	762.54	77.89	2.934	22.3	14.26	10.80	2.0439	55.85	864
C2	20.00	80.00	510	30	796.85	77.67	2.846	23.6	14.08	10.47	2.0811	54.19	843
C2	30.00	70.00	718	40	746.45	69.12	2.737	25.2	13.82	10.06	2.0922	51.92	815
C2	40.00	60.00	755	40	776.83	68.81	2.650	26.6	13.65	9.73	2.1305	50.61	795
C2	50.00	50.00	794	40	805.80	68.40	2.566	28.1	13.49	9.42	2.1727	49.49	774
C2	60.00	40.00	1040	50	737.74	60.22	2.459	29.8	13.24	9.02	2.1871	47.86	747
C2	70.00	30.00	1087	50	763.08	59.80	2.375	31.3	13.08	8.70	2.2289	46.92	727
C2	80.00	20.00	1359	60	789.74	59.60	2.244	35.1	13.08	8.21	2.2148	44.92	740
C2	90.00	10.00	1419	60	813.42	59.16	2.160	36.8	12.93	7.89	2.2557	44.06	686
C2*	100.00	0.00	1476	60	838.77	58.86	2.077	38.5	12.79	7.58	2.2997	43.39	666
C3	0.00	100.00	302	20	799.50	85.97	3.046	20.8	14.52	11.22	2.0358	58.50	892
C3	5.00	95.00	311	20	819.38	85.89	3.011	21.4	14.47	11.09	2.0642	57.82	883
C3	10.00	90.00	321	20	838.29	85.63	2.975	22.0	14.41	10.96	2.0927	57.18	875
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
C4	0.00	100.00	302	20	799.50	85.97	3.046	20.8	14.52	11.22	2.0358	58.50	892
C4	5.00	95.00	311	20	819.37	85.89	3.011	21.4	14.47	11.09	2.0643	57.82	883
C4	10.00	90.00	321	20	838.29	85.63	2.976	22.0	14.41	10.96	2.0941	57.22	875
C4	20.00	80.00	340	20	877.08	85.49	2.910	23.2	14.32	10.71	2.1570	56.17	859
C4	30.00	70.00	359	20	915.87	84.80	2.847	24.5	14.24	10.48	2.2237	55.18	843
C4	40.00	60.00	378	20	955.02	84.59	2.787	25.7	14.16	10.25	2.2940	54.49	828
C4	50.00	50.00	397	20	993.25	84.32	2.730	26.9	14.10	10.03	2.3672	53.92	813
C4	0.00	100.00	302	20	799.50	85.97	3.046	20.8	14.52	11.22	2.0358	58.50	892

* The results obtained for the reference scenario are represented in bold.

* The optimal configuration selected from the Pareto front is represented in red.

Gran Canaria. It is based on:

- the C2 time frame for EV charging (EVs are charged during the central hours),
- 100 % of EVs integrated in the system, or 0 % fuel-based transport,
- an installed PV power capacity of 1476 MW, capable of satisfying 60 % of total electricity demand, and
- an installed wind power capacity of 838.77 MW, capable of satisfying 58.86 % of total electricity demand.

Fig. 9 also shows where the reference scenario is located in each chart (yellow points). It can be seen how the optimization algorithm improves on the reference scenario in all the proposed solutions, reaching the optimal solution in the lower left-hand corner of each chart. This is because when the algorithm is applied it always seeks the maximum RES capacity, in the form of wind and PV power, irrespective of the percentage of EV integration.

Fig. 9d shows the repercussions of EV integration for the system. It can be seen how optimal integration reduces oil consumption from 14.0 TWh to 7.58 TWh, equivalent to a 45.86 % decrease. In terms of CO_2 emissions (Fig. 9b), optimal integration results in a 45.1 % reduction with respect to the reference scenario, from 3.79 Mt to 2.08 Mt. These results are coherent with those obtained in previous studies on another island in the Canary Archipelago of similar dimensions [69]. As can be seen in Fig. 9a, the total annual costs are reduced from 950 M€ to 666 M€, which is equivalent to a 29.9 % reduction. Fig. 9c shows that the PES (total energy required to supply the system) is reduced from 14.84 TWh to 12.79 TWh, which corresponds to a 13.81 % reduction. Fig. 9e highlights the fact that the optimal solution detected is also the most balanced in terms of total annual costs and annual energy storage needs to minimize fossil fuels in the system.

Fig. 10 shows how the most economical scenario for the Gran Canaria electrical system is the one that seeks to produce all the necessary energy through RES and, in turn, EVs are charged during the central hours (C2 time frame).

Fig. 11 shows the Sankey diagram of the optimal scenario obtained after executing the method presented in this paper. A comparison with the Sankey diagram of the reference system (Fig. 3) shows a clear reduction in the global energy needs of the system. It can be seen that the conversion of all passenger cars into EVs results in a more than notable increase in the participation of renewables from 0.57 TWh (Fig. 3) to 3.00 TWh. At the same time, oil consumption throughout the system is substantially lower, falling from 14.0 TWh to 7.58 TWh, as can also be seen in Fig. 9d.

Once the most appropriate scenario was available in EnergyPLAN, it was verified in PowerWorld. In this case, the chosen scenario was the year with the C2 load curve. The hours shown in Table 8 of the summer and winter days of highest and lowest production were modelled and simulated as these are the most critical for the system when it is closest to its upper and lower operating limits.

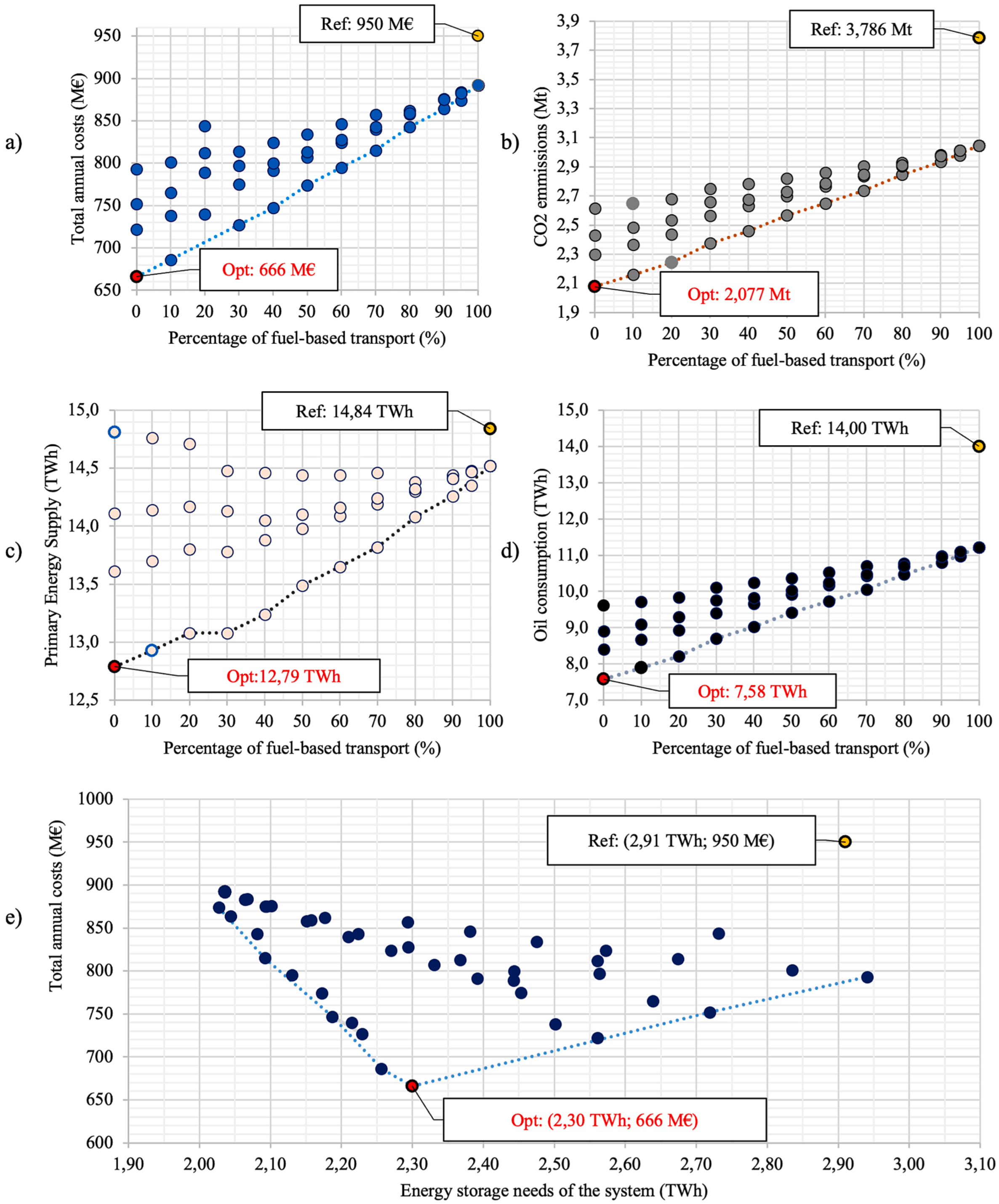

Fig. 9. Optimal solutions and Pareto fronts shown as: (a) Total annual costs (M€) vs. percentage of fuel-based transport (%); (b) CO2 emissions (Mt) vs. percentage of fuel-based transport (%); (c) Total annual fuel consumption, PES, (TWh) vs. percentage of fuel-based transport (%); (d) Total annual oil consumption (TWh) vs. percentage of fuel-based transport (%); and (e) Total annual costs (M€) vs. annual energy storage needs to minimize fossil fuels in the system (import/export intersection value).

Fig. 12 represents the nodes and the different energy sources of the power system of Gran Canaria. It can be seen that there are four nodes with synchronous generators (Bco Tirajana I 220, Bco Tirajana II 220, Bco Tirajana 66 -which are geographically close- and Jinamar 66). The nodes that are located at the top of the figure represent substations with high load and no generation. The nodes that are in the lower and middle part of the image have the highest amount of renewable generation.

Fig. 12 shows the different symbols that appear in the PowerWorld software. The barrel represents the fossil fuel generating units, the wind turbine symbol represents the wind farms, and the sun represents the PV plants. The down arrow represents the load, and the other symbols show the transmission lines, power transformers and nodes.

Table 8 shows the hours that were studied, representing the highest and lowest power demand moments of 2019 with the optimal EnergyPLAN scenario.

Table 9 shows some of the load shedding results that occurred in the electrical power system when a three-phase electrical short circuit was simulated in one of the two selected nodes. These faults were simulated

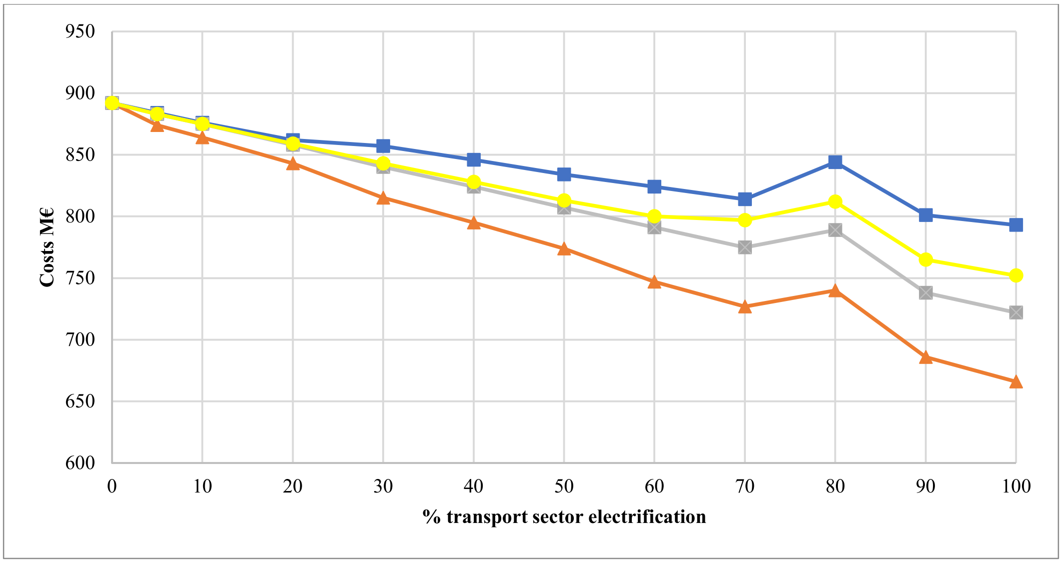

Fig. 10. Total annual costs. Blue line: C1 charging time frame (24:00–08:00). Orange line: C2 charging time frame (13:00–19:00). Grey line: C3 charging time frame (all day and night). Yellow line: C4 charging time frame (24:00–08:00 and 15:00–18:00). Total annual costs are fixed costs plus variable costs.

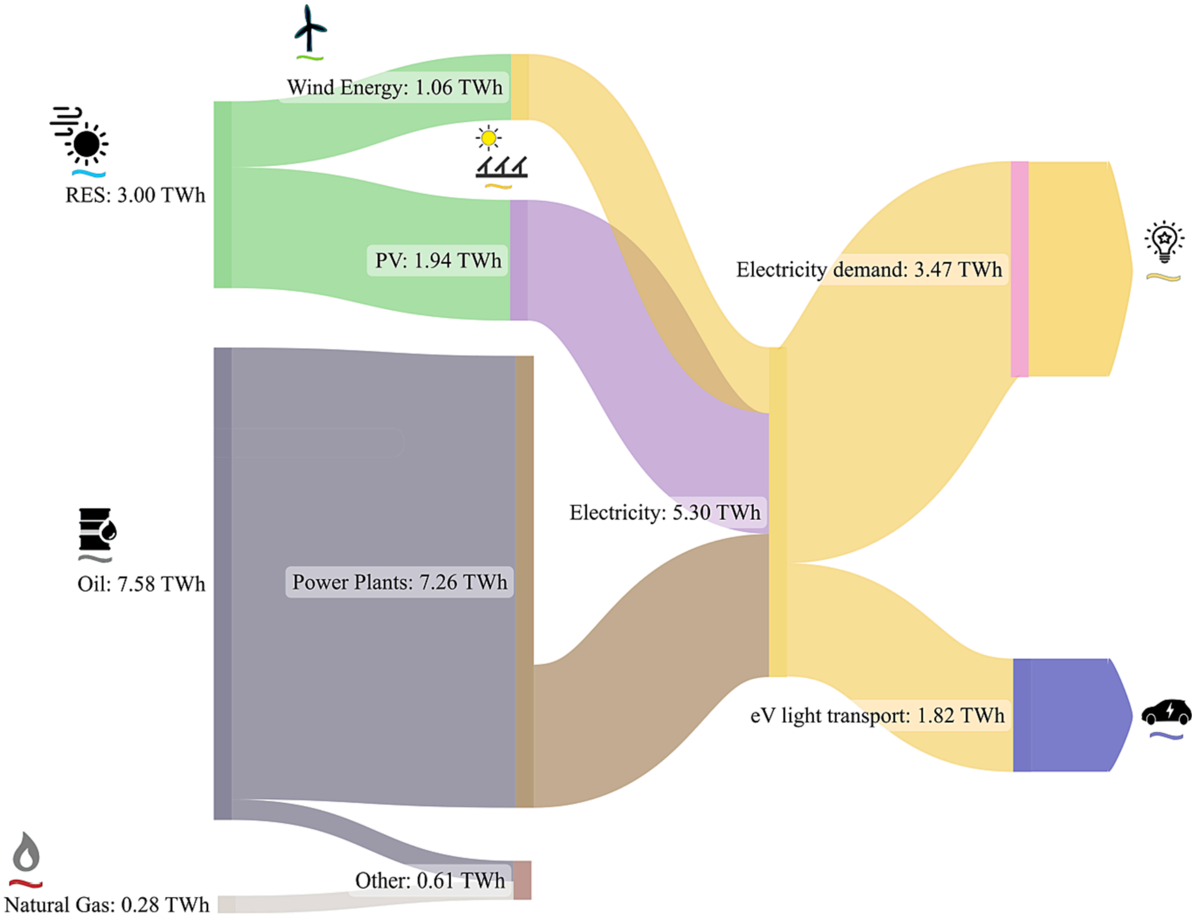

Fig. 11. Sankey diagram of the optimized alternative scenario to power EVs in Gran Canaria (TWh).

in different days/hours of the EnergyPLAN scenarios. The fault was cleared on average around 0.8 s after the short circuit occurred. The smallest CCT obtained in the simulation was 0.1 s and occurred in the peak period on the summer day with the highest power demand, with the same value in both of the tested nodes (SE Guia – SE Matorral). This is a scenario with high power demand and most of the electricity generated is produced by PV energy, with no wind energy contribution. Table 9 also shows that, in all cases, the CCT (the value limit where load shedding values of below 10 % are respected for three-phase short circuits, as indicated in the technical criteria [22]) is acceptable for island

Table 8
Summer and winter days of highest and lowest power demand with the optimal EnergyPLAN scenario.

Simulated scenario	Peak Period	Flat Period	Off-peak Period
Summer day with highest power demand	19/08 13:00	19/08 08:00	19/08 04:00
Summer day with lowest power demand	10/06 13:00	10/06 09:00	10/06 03:00
Winter day with highest power demand	08/01 13:00	08/01 08:00	08/01 03:00
Winter day with lowest power demand	20/01 13:00	20/01 19:00	20/01 04:00

electrical systems.

It can be seen how summer is where the greatest power is demanded and how the days of lower power in summer are approximately as demanding as in winter.

The nodes selected for the purpose of this study were SE Matorral and SE Guía. SE Guia is the furthest node from the biggest power plant in Gran Canaria (Barranco de Tirajana), but also has renewable energy sources and load. SE Matorral is a node that has an important presence of renewable energy and is close to the Barranco de Tirajana power plant.

Fig. 13 shows the frequency variations during a balanced three-phase short circuit (winter day with highest power demand). The fault occurs at t = 0 s and is cleared at t = 0.4 s. The latter number (0.4) is the CCT value for a three-phase short circuit on the winter day with the highest power demand in the SE Matorral node. Initiaaly, the frequency rises because the network voltages V_i drop and, consequently, the generators see only a reduced load. The frequency of the power system and the velocity of the conventional synchronous units are proportional. At t = 0.4 s the fault is cleared and the network voltages V_i recover, causing the generators to see a higher load and reduce their rotational speed. If the frequency decreases beyond a preset value, some of the load is shed, helping stabilization of the system. The load shedding relay is activated when the frequency value is lower than 48.9 Hz (0.94p.u.). If more than 10 % of the load that the power system demands in that instant is shed, it can be considered that the scenario is not complying with the standard that the TSO expects. After the load shedding relay is activated, the system and its generating units stabilize the frequency, but it does not climb back to 50 Hz.

Fig. 14 shows how the short circuit affects the entire grid. It can be seen how, as the short circuit causes the voltage at the site where the fault occurs to fall to zero, the voltage falls substantially throughout the grid. When the fault occurs, the electrical powers of the generators connected to that node (P_e) also decrease because of the effect described in Eq. (6). This, in turn, causes the generators to speed up because of the imbalance between mechanical and electrical power. However, as soon as the fault is cleared, the initial value is recovered in less than 3.5 s.

The results obtained with the method developed in this research allow some optimism when it comes to technical validation of the results obtained in planning studies that seek high RES integration through electrification of the transport sector, as in the case study presented here. Nonetheless, full validation of such studies would require additional electrical analyses which may well suggest, as well as the strategies suggested in this research, improvements to the electrical infrastructures of the conventional grid to enable any proposed changes to be implemented. This should be borne in mind when assessing the real costs of implementing such strategies. Likewise, the considerable reductions in oil consumption and CO_2 emissions obtained in the present study may be limited by the start-up and response times of the current generation system in Gran Canaria, as also pointed out in [69] for the island of Tenerife. It should be noted that, although the method has been designed for application to the entire transport sector, in the case study of Gran Canaria considered in the present study only passenger vehicles were considered. Nonetheless, the results obtained in terms of renewable integration, reduced costs, reduced oil consumption, etc., are very positive. Therefore, the inclusion of other vehicle types could improve the results even further.

For future research, we therefore recommend inclusion in the method of new stationary and dynamic studies which consider the need for grid improvements to absorb any new renewable plants that might be proposed by the algorithm, as well as the incorporation of any such

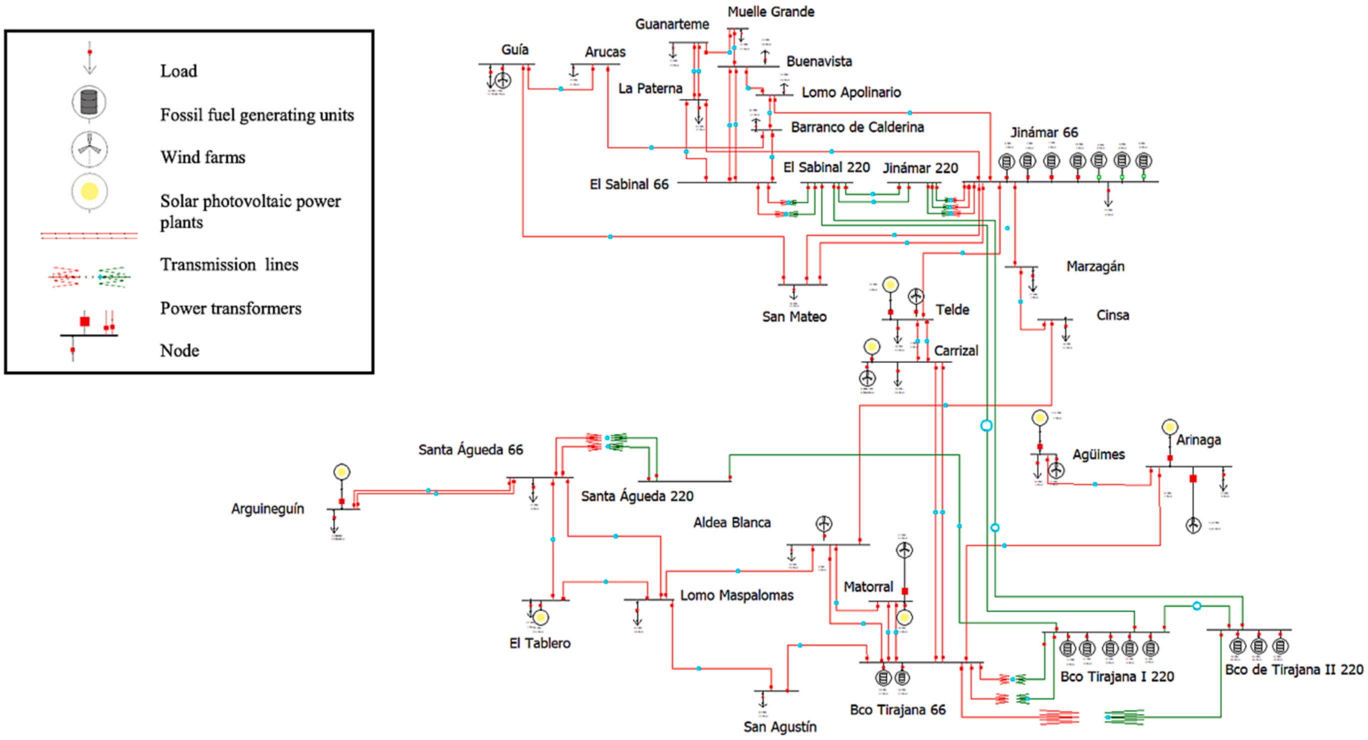

Fig. 12. Single line diagram of the electrical power system of Gran Canaria modelled in PowerWorld.

Table 9
Load shedding and CCTs obtained for the Gran Canary electricity system in the scenario where all the transport is electrified and all the energy demand to meet this load comes from renewable energy sources.

	Load Shedding (MW)			CCT (s)		
SE GUIA	**Peak Period**	**Flat Period**	**Off-peak Period**	**Peak Period**	**Flat Period**	**Off-peak Period**
Summer day with highest power demand	149.57	58.24	37.44	> 0.1	> 1.3	> 1.1
Summer day with lowest power demand	121.44	59.36	37.17	> 0.3	> 1.3	> 0.7
Winter day with highest power demand	123.84	50.04	38.13	> 0.8	> 1.4	> 0.7
Winter day with lowest power demand	116.76	63.14	36.68	> 0.7	> 1	> 0.7
SE MATORRAL	**Peak Period**	**Flat Period**	**Off-peak Period**	**Peak Period**	**Flat Period**	**Off-peak Period**
Summer day with highest power demand	149.57	58.24	37.44	> 0.1	> 1.2	> 0.7
Summer day with lowest power demand	121.44	58.67	27.62	> 0.7	> 1.2	> 1.3
Winter day with highest power demand	123.84	50.04	32.68	> 0.4	> 0.7	> 1.2
Winter day with lowest power demand	116.76	52.56	31.44	> 0.8	> 0.7	> 1.4

proposed grid improvements in subsequent economic assessments. We also recommend the application of this method to a complete case study which includes all the types of transport immersed in the system and not just passenger vehicles.

4. Conclusions

A method to create optimal transition scenarios and validate their electro-technical performance has been developed. The aim was to find a method which produces an electrically validated scenario with electrification of the transport sector which is also optimal from an economic perspective. The island of Gran Canaria (Spain) was used as case study, considering only the passenger cars on the island. A total of 5808 scenarios were simulated with different renewable energy productions, electrical transport sector demands and EV charging time frames. The optimal energy scenario was then calculated and simulated in PowerWorld based on the 2019 layout to verify its proper functioning within the power quality parameters established by the TSO.

Results show that the optimal scenario is attained when the transport vehicles considered are fully electrified and all the electricity demanded comes from renewable energy sources. This would in turn mean a 45.86 % oil consumption reduction from 14.0 TWh to 7.58 TWh. In terms of CO_2 emissions, electrification of the transport sector under these optimal conditions would allow a 45.1 % with respect to the reference scenario. In addition, there would be a 29.9 % reduction in the total annual costs of the energy system model analysed for Gran Canaria and a 13.81 % reduction in the total energy required to supply it.

Additionally, it was found in this study that charging the vehicles when wind and PV energy are highest (C2 time frame) was found to be the most economically feasible option. The results support the initial hypothesis that the need for more renewable energy installations increases with electrification of the transport sector, making generation costs lower. The study of the electrical power system shows that, under certain conditions, the optimal EV and renewable generation percentage penetration scenarios in the EnergyPLAN simulations would meet TSO grid criteria. The electricity system of Gran Canaria could withstand significant EV penetration and renewable energy production without exceeding 10 % of load shedding. For future research, we therefore recommend inclusion in the method of new stationary and dynamic studies which consider the need for grid improvements to absorb any new renewable plants that might be proposed by the algorithm, as well

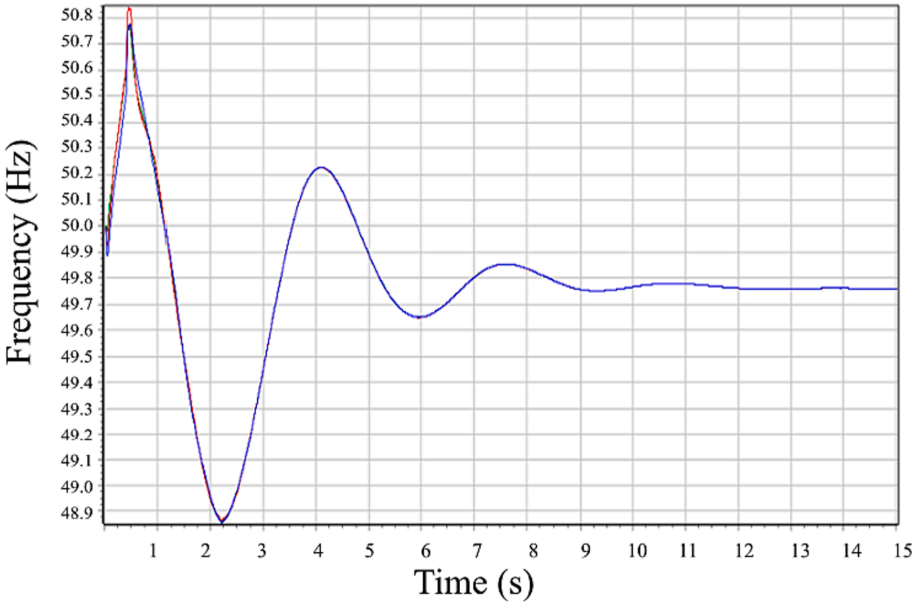

Fig. 13. Frequency variations during a balanced three-phase short circuit (winter day with highest power demand).

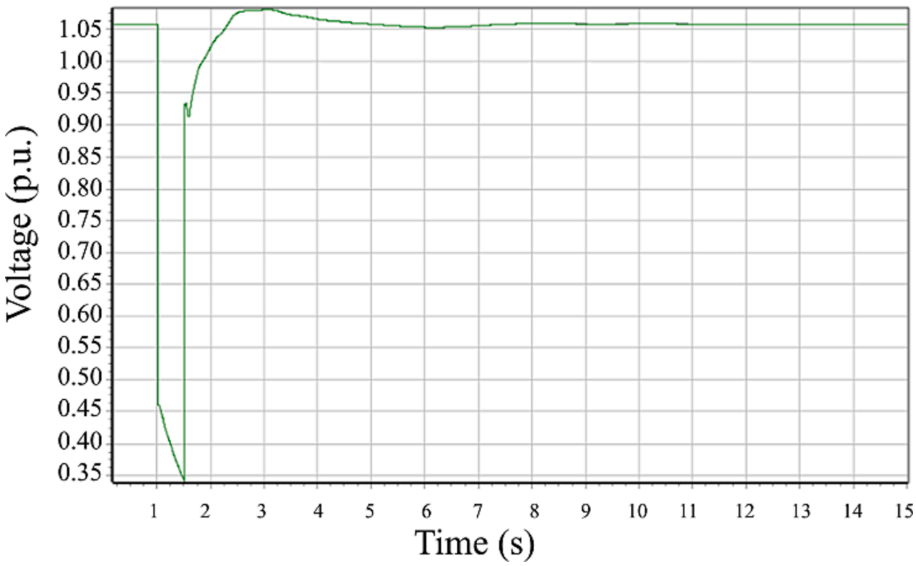

Fig. 14. Network voltage drop during a balanced three-phase short circuit (winter day with highest power demand).

as the incorporation of any such proposed grid improvements in subsequent economic assessments. We also recommend the application of this method to a complete case study which includes all the types of transport immersed in the system and not just passenger vehicles.

CRediT authorship contribution statement

Alejandro Jiménez: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft preparation, Writing – review & editing, Visualization. **Pedro Cabrera:** Conceptualization, Methodology, Software, Investigation, Validation, Formal analysis, Resources, Writing – original draft preparation, Writing – review & editing, Visualization, Supervision, Project administration. **José Fernando Medina:** Conceptualization, Methodology, Software, Investigation, Validation, Formal analysis, Resources, Writing – original draft preparation, Writing – review & editing, Visualization, Supervision, Project administration. **Poul Alberg Østergaard:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft preparation, Writing – review & editing. **Henrik Lund:** Software, Resources, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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