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Smart renewable energy penetration strategies on islands: The case of Gran Canaria

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ABSTRACT

This paper presents a new method, based on the *Smart Energy Systems* concept. The aim is to increase the share of renewable energy penetration on islands. The method is applied to the island of Gran Canaria (Spain), considering the entire energy system of the island. Several *smart renewable energy strategies* are proposed following a cross-sectoral approach between the electricity, heating/cooling, desalination, transport and gas sectors. The different smart renewable energy strategies were applied in a series of steps, while looking for a transition from the current energy system to a nearly 100% renewable energy system. Based on the results, the study concludes that the suggested method is applicable for increasing renewable integration on islands and can potentially be used in helping energy planners to take decisions about priorities in development of the sector to improve such integration. The results indicate that, for the case of Gran Canaria, a 75.9% renewable energy system could be attained with technologies that can be implemented at present. Furthermore, it is shown that a nearly 100% renewable energy system in Gran Canaria is technically feasible and could be achieved if certain technologies acquire greater maturity.

1. Introduction

There is a general consensus that energy systems will need to change in a near future [1]. On this basis, there are several reasons to consider the implementation of renewable energy solutions in energy systems worldwide [2]. As well as energy security, long-term environmental, economic and developmental goals are behind the desire to replace fossil fuels with renewable energy based technologies [3]. Furthermore, the implementation of renewable energy systems can contribute to strengthening and improving other social issues, including democracy and living conditions in local communities [3].

Several authors have underlined the benefits of renewable energy integration in energy systems [1], and while these are evidently important in large-scale energy systems they could be essential in islanded energy systems [4]. Insularity, in general terms, means higher transport, communication and energy costs compared to continental regions [5]. Most islands in the world depend on fossil fuel importation and, in many cases, this has a negative impact on the island's energy security as well as its economy, environment and development. The main limitation for the introduction of renewable energies is the intermittent nature of the wind and solar energy supply. Hence, one of the major challenges for the adoption of renewable energy solutions is how to combine such intermittent resources into a single hybrid energy system [6]. This issue, together with the characteristic small-size energy systems of islands, are key barriers for the penetration of renewable energy solutions in an island's energy system [4]. For the above reasons, proposals concerning the integration of such technologies are usually accompanied by sophisticated analyses which aim to ensure continuity of the required supply. Cross et al. [7] conducted an extensive bibliographic search which revealed several studies in the scientific literature on increasing the share of renewables in islands. Some of these studies use the RenewIslands analysis approach introduced in Ref. [8]. This methodology provides a framework for mapping the island's needs and for the assessment of alternative scenarios in energy and resource planning on island energy-systems [8,9]. Studies carried out for Porto Santo island (Portugal) [5], Mljet island (Croatia) [10] and Hvar island [11] are a few examples which use this methodology to

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Nomenclature

BAU	Business-as-usual
CHP	Combined heat and power
EEP	Excess electricity production
ERDF	European Regional Development Fund
eV	Electric Vehicles
GIS	Geographic Information System
ISTAC	Spanish initials: Canary Islands Institute of Statistics
MSF	Multi-stage flash
PES	Primary energy supply
PHES	Pumped-hydroelectric energy storage
PV	Solar photovoltaic
REE	Spanish initials of the TSO in Spain: Red Eléctrica de España, S.A.U.
RES	Renewable energy sources
SCs	Synchronous compensators
TSO	Transmission system operator
V2G	Vehicle-to-Grid

simulate and analyse a 100% renewable energy-system on small-sized islands. Likewise, studies have been undertaken with similar goals for Malta [12], Lesbos [13] or Salina [14]. It should be noted that this problem has also been tackled using other approaches, including the use of a geographic information system (GIS) to identify the renewable potential in small islands [15], the use of an imaginary island to highlight the strengths of various renewable integration techniques [16] or the proposal for a design and sizing method of hybrid power plants in autonomous insular power systems for the maximization of renewable energy sources (RES) penetration [17]. Nevertheless, all these studies undertaken to date tackle the problem of the maximisation of renewable penetration on islands by focussing in particular on one of the sectors that form part of the energy system, usually on the electricity sector. Very few studies, which include publications by Segurado et al. in Refs. [4] and [18] and Katsaprakakis et al. in Ref. [19], consider any other energy sector and couple the electricity and water supply systems to increase the penetration of renewables. These authors use the intermittent surplus generated in the electricity system by renewable resources to supply the desalination and pumping units, but they only combine and study two sectors, which limits the actions that can be taken. Finally, just one study, by Gils and Simon [20], provides a cross-sectoral pathway to transform the energy supply system towards a 100% renewable energy system for a set of islands (the Canary Island archipelago). However, these authors, instead of tackling the problem of increasing RES participation in one particular island, interconnect all the power systems of the different islands using several submarine power transmission lines and analyse the grouped together energy systems for the transfer of surplus/deficit energy from one island to another. This solution shows a good performance, but the results are strongly conditioned by the proposed power system transmission interconnections and the implementation of this solution is very difficult to carry out because of the distances involved between islands and the considerable depth of the sea floor. In addition, use of such a strategy and the optimization methodology employed, make this a very site-specific study and reduce its applicability to a limited number of archipelagos in the world. Finally, while the study is extensive and ascribes the strategies to three large groups, the contribution of each sector/technology to increasing RES in the energy systems of the island system remains unclear.

However, to date no island-based studies have been published which tackle the problem of maximising renewable penetration considering the proposal of strategies which increase the interconnectivity of the different sectors to make the system more flexible and to cushion the effect of the intermittent nature of energy coming from renewable sources. Likewise, no study has to date been carried out which analyses the unitary contribution made by strategies implemented on each of the sectors involved in a stand-alone energy system. In other words, never before has the potential of the different sectors involved in a completely isolated energy system to raise renewable penetration been evaluated. For these reasons, the main aim of this article is to close this gap of knowledge detected with the application of a novel method which uses a series of smart renewable energy strategies that combine actions in all the energy sectors that operate on islands. This innovative formulation is based on the *Smart Energy System* concept, first described in 2012 [21]. As opposed to, for instance, the *Smart Grid* concept, which puts the sole focus on the electricity sector, the approach used by smart energy systems takes into account the entire energy system along with the identification of suitable energy infrastructure designs and operational strategies [22]. This method was applied using a technical optimization procedure which implements a novel algorithm to search for the optimum configuration of renewable installations with the lowest possible energy surplus/deficit.

The proposed approach is applied to the island of Gran Canaria (Spain), as case study, but can be applied to any isolated energy system throughout the world. For the specific case study considered here, never before has an approach similar to the one proposed in this study been used. This island is a very interesting to use, as its energy system is almost totally dependent on fossil fuels imported from external countries [24]. Local particularities, including the large population of the island, the year-round impact of a huge number of tourists, and its remoteness in relation to the European continent, tend to further aggravate the problem is this dependence. The lack of its own conventional energy sources and a limited supply of water are further reasons to consider the implementation of renewable energy systems. However, Gran Canaria has excellent potential in terms of renewable energies. The abundant solar resource [25] and wind resource [26,27] on the island comprise an excellent opportunity for the development of a new local renewable energy system. Today, this renewable potential remains relatively unexploited given the current very limited contribution of renewable sources to the energy balance of the island [24]. To date, for the island of Gran Canaria, the only proposals made to increase the integration of renewable energies have involved the electric subsystem. More specifically, in Ref. [28] an analysis is made of the water resources and terrain topography of the island and the results are presented of a model which optimizes the sizing of a proposed wind powered modular hydro-pumped system to cover a percentage of peak demands using already existing reservoirs as storage deposits. In Ref. [29], the use of a pumped hydroelectric energy storage (PHES) system is also proposed, but in this case the solution is applied to a small remote region on the island called *"La Aldea de San Nicolás"*. That study proposes, instead of using two reservoirs to store the water, combining a seawater pumping system with the use of a single reservoir. Similarly, in Ref. [30] a double storage system is proposed based on a hydrogen storage system and a desalination plant to increase the renewable supply of another very small remote region on Gran Canaria, called *"El Risco"*. Finally, in Ref. [31], a study was undertaken of the effects of incorporating a PHES system on RES penetration of the island's electric system. That study was tackled from the perspective of ensuring grid security and stability and concluded that: i) the PHES allows an increase in the wind penetration level on the island; ii) the PHES improves the steady-state operation conditions of the power system; and iii) in case of a disturbance, the PHES improves system stability. Although these four studies obtain considerable increases in RES penetration in the electric system, they are centred solely on the electric system and, therefore, the increase of the RES share with respect to the whole energy system is limited. The present study, for the first time, considers optimization of the operation of the energy system in its entirety, analysing the overall potentialities/requirements of the system to interconnect the different sources of energy supply, demand and storage of the various sectors in the energy system (electricity, heating/cooling, water supply, transport, gas, etc.).

The authors of the present study believe that it can serve as a reference point for other similar islands around the world, and that the extensive analysis undertaken can serve as a roadmap for future planners of scenarios aiming for a higher participation of renewable energies in stand-alone energy systems. Additionally, this work reports notable increases in renewable penetration in the system after the application of strategies in sectors that have not previously been studied for the island of Gran Canaria and, therefore, it can justifiably be argued that this work also serves as a starting point for more detailed analyses in the different sectors considered.

2. Methods

This section describes the basic principles, the tool employed and the procedures which form the basis of the proposed method to increase renewable energy penetration in a relatively small and completely isolated energy system, as is the case of an island. This method, which is inspired by the application of the *Smart Energy Systems* concept to larger systems [1], presents certain novelties and settings which make it applicable to islands.

2.1. Basic principles of the method

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

1. The considered approach involves all the energy system sectors of the island, namely electricity, heating/cooling, desalination, transport and gas. This is essential for implementation of the *Smart Energy Systems* concept, because the fundamental objective of this theory is to take advantage of possible synergies by combining all sectors of the energy system [1].
2. Due to the inherent fragility of small-sized isolated electric systems (islands), a balanced energy system configuration, with a lower RES share, will be preferable to an energy system with a higher RES share but which is unbalanced. This fact, along with the purely technical approach of the present study, determined the way of choosing the optimum RES configuration for each analysed alternative. To be more specific, a technical optimization criterion was used based on equalling and minimizing the sum of the energy surplus – defined as excess electricity production (EEP) [1] – and the lack of energy when meteorological conditions are insufficient to meet demand with RES.
3. A short-term (hourly) approach in the analysis of the behaviour of intermittent RES – as is the case with wind and solar photovoltaic (PV) power – and energy demand is considered in order to take into account the fluctuating nature of these energy

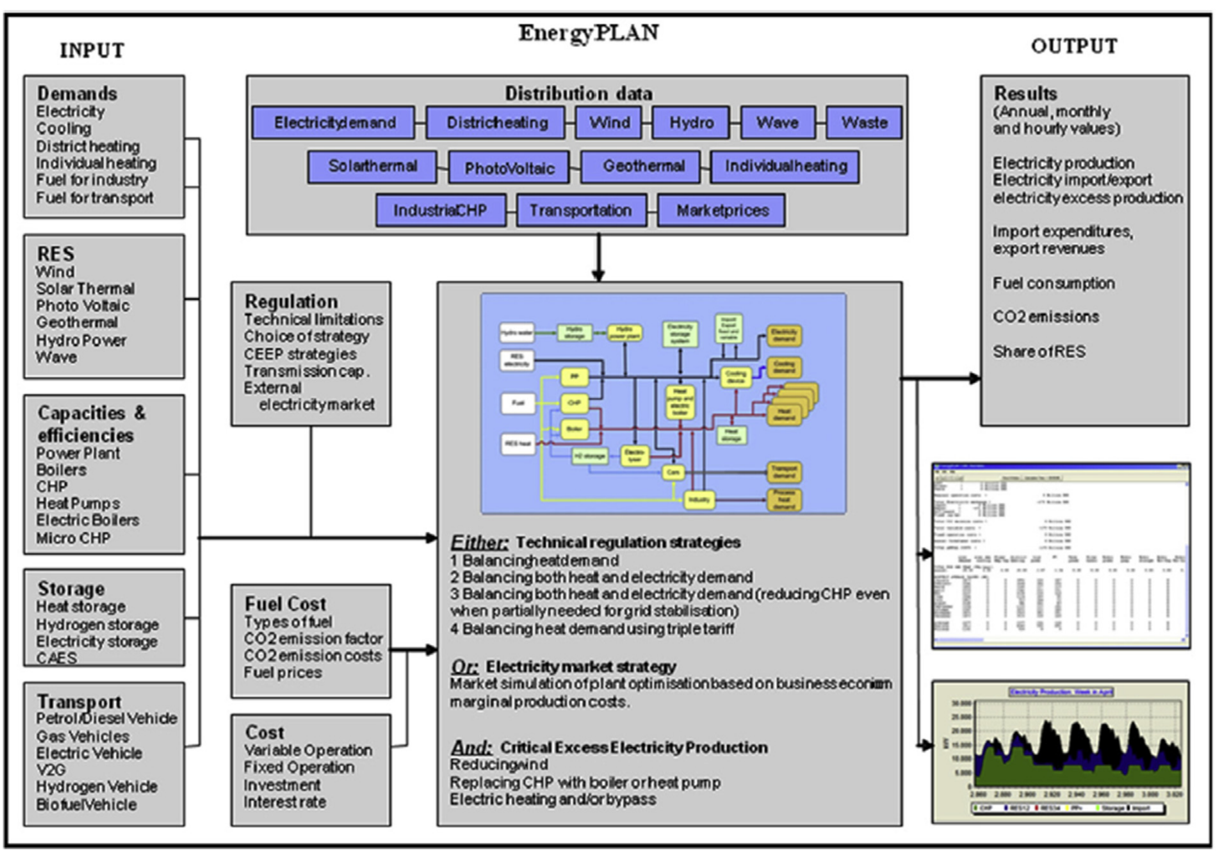

Fig. 1. The EnergyPLAN Energy System Analysis model structure [23].

sources and the potential for making demand more flexible, in this way adapting it to the intermittent nature of these RES.
4. Testing different alternative solutions is important given that the objective pursued through the analysis described in this paper is not an easy one and may require the use of technologies that are still in the early stages of development.

In essence, the particularities and requirements of this method share the *"Choice Awareness"* theory propositions [32] which are linked with the energy analysis tool used and the Smart Energy Systems concept, but incorporating a new approach which makes it applicable to islands.

2.2. The energy analysis tool

EnergyPLAN [33] is an input/output deterministic energy system analysis tool (see Fig. 1) specifically designed to assist the design of national or regional energy planning strategies under the *"Choice Awareness"* theory [1]. As indicated in Ref. [33], EnergyPLAN is disseminated as freeware and is used by many researchers, consultancies, and policymakers worldwide. Descriptions of the algorithm can be consulted in the different manuals, reports and documents published on the website www.energyplan.eu. Some authors consider this software to be the most suitable available tool for identification of how renewable energies can be integrated into a defined energy system [34]. It is one of the most commonly used tools for the evaluation of high-RES energy systems [35]. Numerous studies, including those by Østergaard [35] or Connolly and Vad Mathiesen [36], have highlighted the possibilities of EnergyPLAN. This tool simulates the electricity, heating/cooling, desalination, transport and gas sectors, with a view to integrating each primary sector of the energy system within an hourly approach [37]. Additionally, from this software it is possible to balance the energy system and to analyse how new smart strategies applied in one sector can affect others. The EnergyPLAN model has, as general inputs, the demand, the renewable energy sources, the energy station capacities, the costs and the number of optional regulation strategies [37]. Among the various outputs are energy balance and resulting annual production, fuel consumption, electricity import/export, total annual carbon dioxide emissions, etc. More information and detailed descriptions can be found in Refs. [23,33].

The authors acknowledge the existence of other models [38] but, given that the purpose of the present article is not to compare the results obtained by different models, the decision to opt for the EnergyPLAN model was based on the significant support in the literature for this model [35] and its relationship to the methodological approach proposed for the present study. As previously mentioned, most studies which have tackled the problem of the maximisation of renewable penetration in islands have applied the RenewIslands methodology [39] which is fundamentally based on the H_2RES model [40]. This model would, therefore, be the ideal candidate for a comparison with the results obtained using the model chosen for the present study (EnergyPLAN). In this respect, the methodological approaches and results of the two models have previously been compared with the purpose of identifying mutual benefits and improvements when analysing the same case study (the island of Mljet, Croatia) [41]. The comparison focussed on a field of analysis shared by the two models, the electricity sector. The models showed small differences with respect to this sector, and, one of the clear conclusions was that, even though the two models had different focusses and historical backgrounds, they both obtained more or less the same results when analysing the same cases.

2.3. The methodological approach for the development of smart renewable energy penetration strategies on islands

The method proposed in this article will follow the structure outlined in the diagram shown in Fig. 2. This structure follows the typical design process used in EnergyPLAN [42] to which, in addition, an optimum RES configuration search has been incorporated so that each proposed alternative is balanced and potentially applicable to islands. The steps followed are described below:

1. The reference energy system to be studied is identified. A real reference scenario is chosen, for which official and verified data and reports are available. All the distinctive features are analysed in detail, and the demands of the different sectors are identified as well as the potential modifications and potentially exploitable energy supply sources in each of them.
2. The results of the model created for the reference energy system are validated. The operating strategies of the reference system are modelled, simulated and adjusted with the analysis tool (EnergyPLAN) until the inputs and outputs correspond to the specifications of the official energy reports of the place in question.
3. New alternatives are proposed in each of the sectors and new *smart renewable energy strategies* are implemented in each of them.
4. A search is made for the RES configuration which obtains a minimum intersection between fossil fuel requirements (imports) and energy surpluses (exports).
5. When the aim of step 4 has been achieved, step 3 is repeated and new alternatives are proposed exploiting the highest number of resources that each sector offers. When the

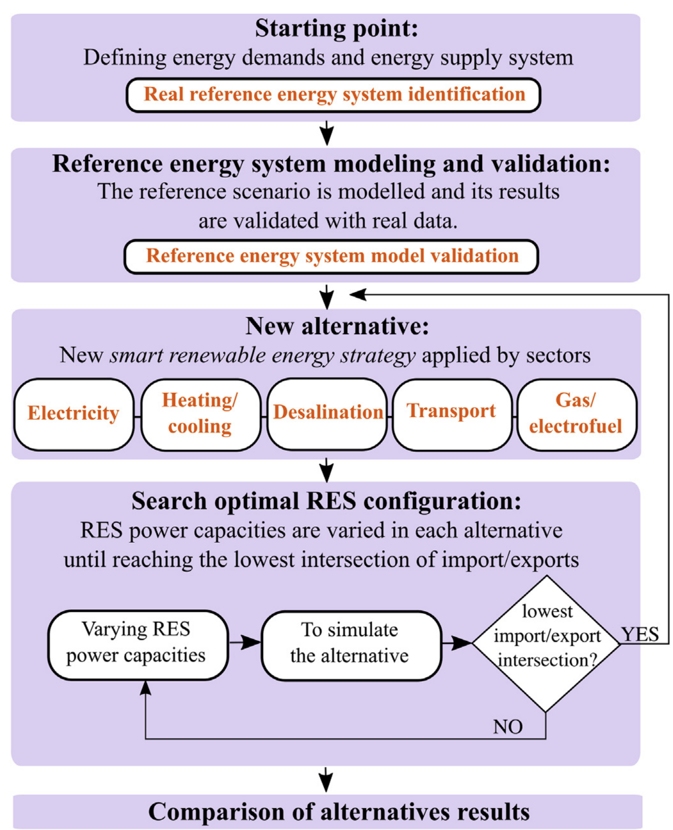

Fig. 2. Outline of the proposed approach to increase renewable energy penetration on islands using the Smart Energy Systems concept.

possibilities in each sector are exhausted, the process moves onto another sector and the same procedure is applied in an aggregated manner.

6. The results are analysed, and the advantages and disadvantages of the alternatives are compared with each other. The results are also compared with other scenarios such as business-as-usual (BAU) or any other alternative scenario under discussion.

3. The island of Gran Canaria as case study

To test the presented method, its application to the island of Gran Canaria is taken as a case study. As can be seen in Fig. 4, firstly the reference energy system chosen for Gran Canaria is analysed (real scenario of 2014), and any potential modifications to increase the RES contribution are set out. Then, to validate the model, the reference scenario is analysed, and the results are compared with the real data published in the official reports of 2014. Subsequently, the new alternatives proposed for each sector are implemented, optimizing the RES configuration in each of them, and the results are analysed. Finally, a comparison is made of the results obtained for the BAU scenario proposed by the Canary Government with the results obtained for the same energy system using this methodological approach.

3.1. Identification of the energy system of Gran Canaria

The island of Gran Canaria is part of the Canary Archipelago, an Autonomous Community in Spain and designated an Outermost Region of the European Union. It is located in the Atlantic Ocean about 150 km off the northwest coast of Africa and about 1350 km from Europe (Fig. 3). Its total surface area is 1560.10 km^2, which corresponds to 20.95% of the territory of the Canary Islands [43]. In 2014, Gran Canaria had a population of approximately 850,000 [43] and 3.59 million tourist visitors [44] (the average number of tourists/month was 299,271, with a low of 215,293 in June and a high of 374,792 in March). As well as some tourism in the capital city in the north, the major tourist resorts of Gran Canaria are found in the south of the island, stretching from Tarajalillo to Puerto de Mogán (Fig. 3).

The total primary energy supply (PES) distribution for the energy system of Gran Canaria in 2014 is shown in Fig. 5. As can be seen, fossil fuels represented 96.2% of total primary energy [24], demonstrating the island's high dependence on fossil fuels.

The electrical system of Gran Canaria consists of an isolated network with two thermal power plants and 42 substations [31]. In 2014, the island had a total electricity demand of 2.63 TWh with a peak load of 544.6 MW in October and a minimum load of 241.2 MW in February (Fig. 8). This demand was covered with an installed total net power capacity of 1036.95 MW, distributed as shown in Table 1 [24].

Shown in Figs. 6 and 7 are the mean hourly wind and PV power distributions, respectively, in all the energy system of Gran Canaria during 2014. The onshore and offshore wind resource of Gran Canaria can be seen in Fig. 9.

The heat demand in Gran Canaria for 2014 was 0.63 TWh, most of which was spent on water heating (83.1% of total heat demand).

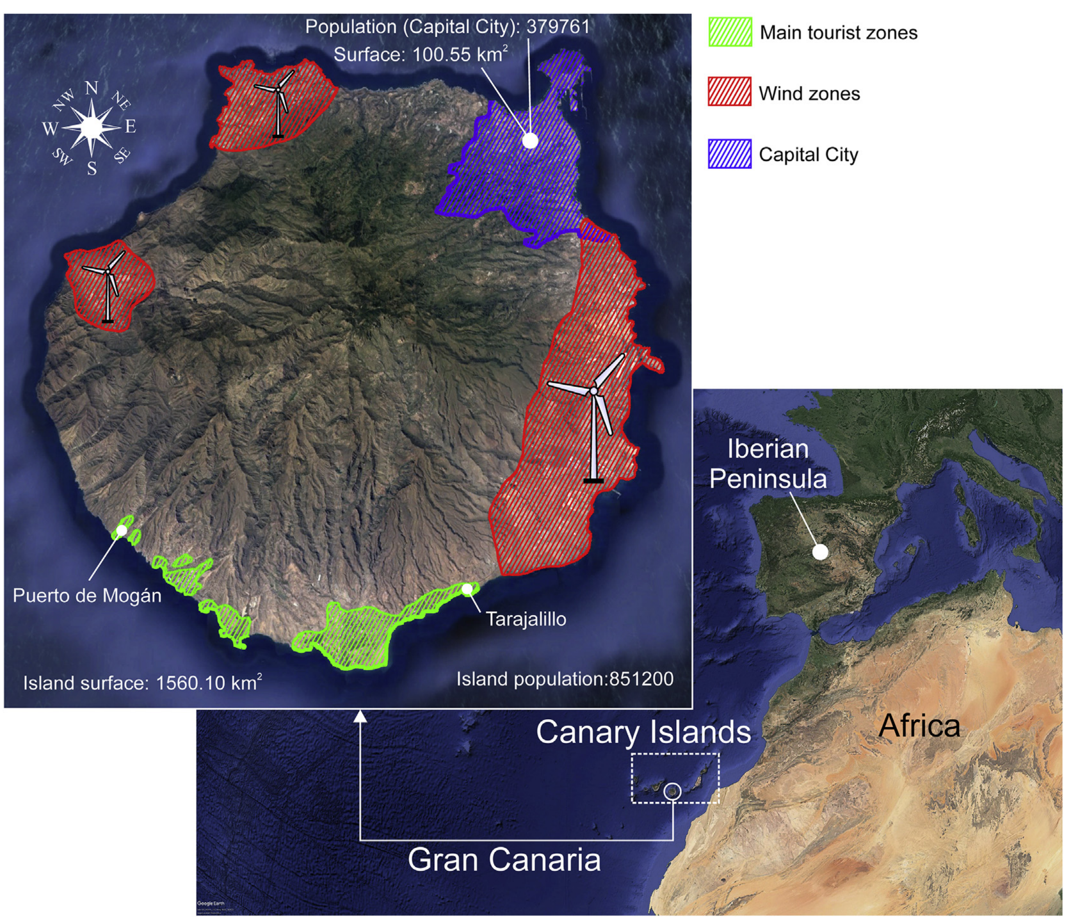

Fig. 3. Main data on the island of Gran Canaria pertinent to this study. [Source of satellite images: Google Earth: ©2018 Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Ladsat/Copernicus, IBCAO ©2018 GRAFCAN].

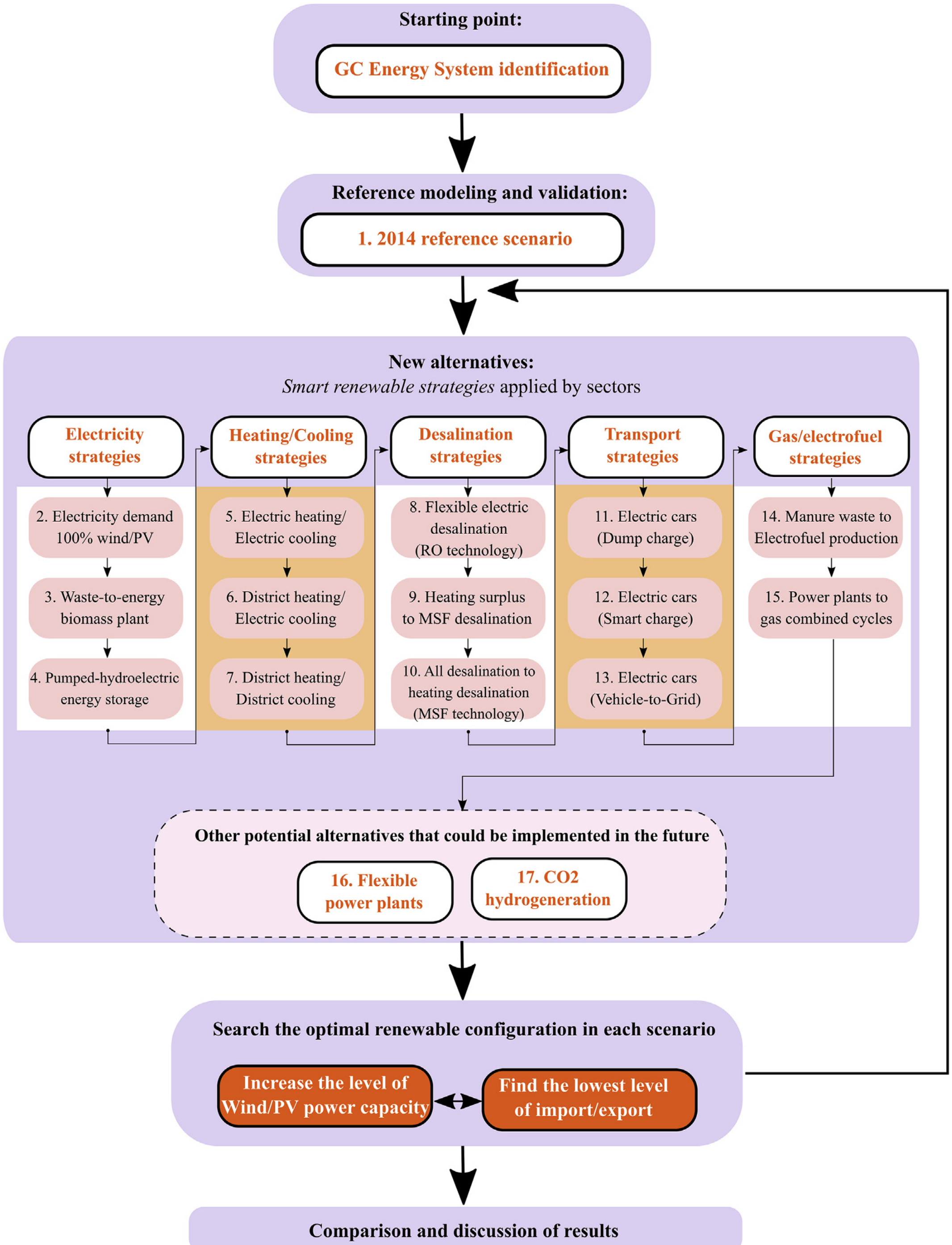

Fig. 4. Approach followed to apply the method and to increase renewable energy penetration in Gran Canaria.

The required energy supply for water heating demand was shared between natural gas (33.6%), individual electric heating (33.4%), oil (22.4%) and solar-thermal (10.6%). Bearing in mind the hourly distribution of temperature in Gran Canaria in 2014 shown in Fig. 10, estimation was made of the distributions of heat demand (Fig. 11) and cooling demand (Fig. 13) considering the annual data of both consumptions and the reference temperatures based on which the artificial heating or cooling systems are activated [24,47]. The mean hourly heating distribution considered (Fig. 11) was estimated distributing the sum of the annual space heat demand (0.103 TWh) and the annual hot water demand (0.524 TWh) of the island [47], according to the real measured hourly temperature (Fig. 10). When this passed the reference temperature (18 °C) activation of the space heating systems was considered, consuming a power proportional to the difference between the reference temperature and the hourly temperature at that moment. The cooling distribution (Fig. 13) was similarly estimated, distributing the annual space cooling demand of the island (0.39 TWh) according to the real measured hourly temperature (Fig. 10). When this passed a reference temperature of 22 °C, connection of the cooling systems was considered as well as their power consumption proportional to the differences between the reference temperature and the real

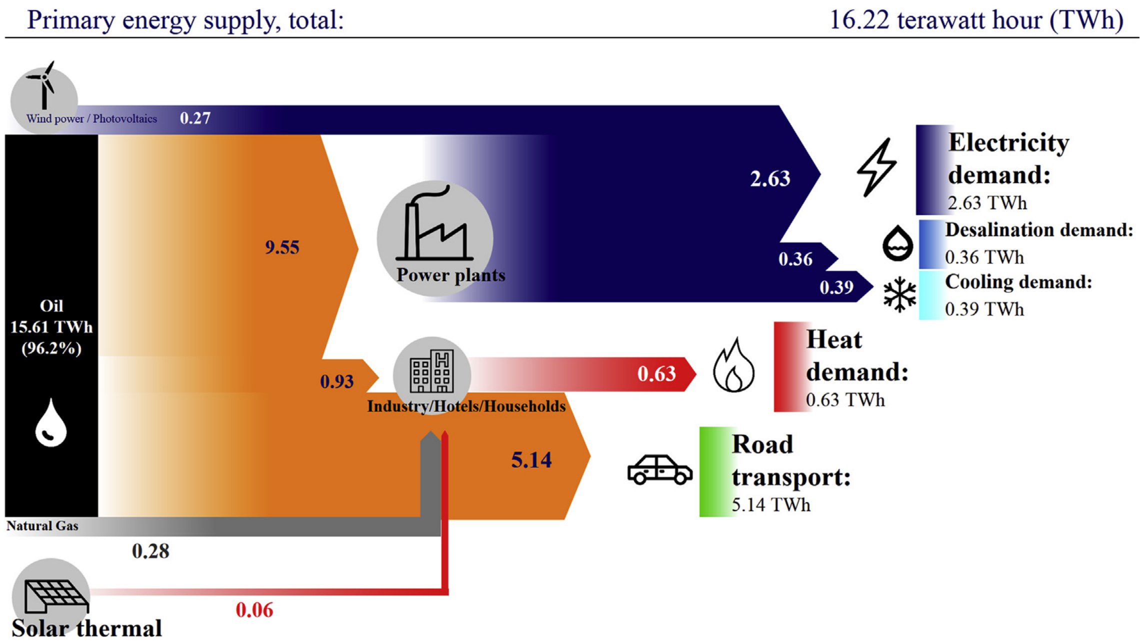

Fig. 5. Total PES of the energy system of Gran Canaria.

Table 1
Installed capacities in the electric system of Gran Canaria in 2014 [6].

Technology	Fuel	Capacity (MW)
Steam turbines	Fuel oil	259.60
Diesel engines	Fuel oil	41.02
Diesel engines	Gas oil	25.53
Gas turbines	Gas oil	147.00
Combined cycle	Gas oil	438.50
Wind	–	85.90
Photovoltaic	–	39.40
	Total:	1036.95

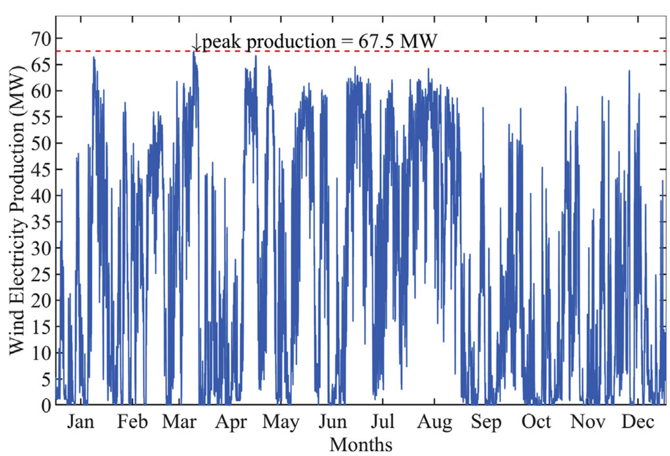

Fig. 6. Mean hourly wind electricity production in Gran Canaria, 2014.

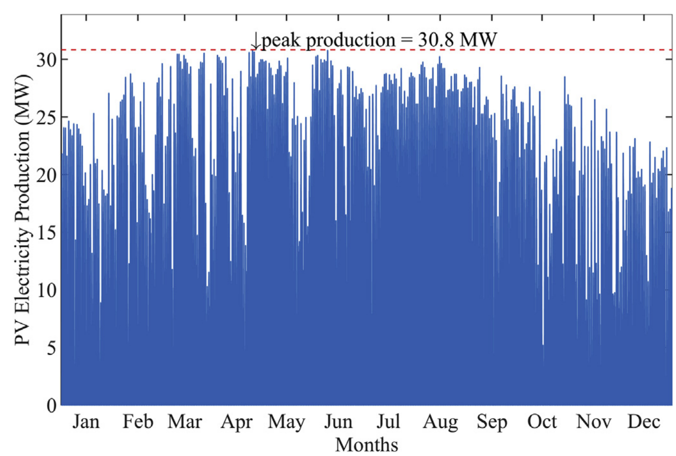

Fig. 7. Mean hourly PV electricity production in Gran Canaria, 2014.

temperature.

The transport sector was completely powered by oil, with a total annual consumption of 5.14 TWh. Some 54.2% of this consumption (2.78 TWh) was powered by petrol and the remaining 45.8% (2.35 TWh) by diesel (0.56 TWh to power (diesel) cars and 1.79 TWh other kinds of (diesel) vehicles) [24]. Air and maritime transport requirements are extremely high and represent an important source of fuel consumption. However, the particularities and location of the island of Gran Canaria make this fuel consumption an international issue. This is the reason why air and maritime transport fuel consumption is not considered in the present study.

Given the vital importance of tourism for the island, considered the driving force of the economy, and the very weak weight of the industrial sector, the mass media in the Archipelago and indeed the Autonomous Government of the Canary Islands generally use the term ‘tourist industry’ to refer to this sector. Given that the highest energy consumption and greatest activity pertain to hotels, industry and hotels have been included in the same group. The fuel consumption of this group was distributed in 0.13 TWh (11.7%) to power diesel machinery, 0.60 TWh (54.1%) of diesel to power transport, 0.196 TWh (17.6%) to power fuel oil equipment and 0.184 TWh (16.5%) to serve natural gas demand [24]. The sum of these values corresponds to 1.11 TWh. It can be seen that in this group the main energy sources used are oil (0.93 TWh), which

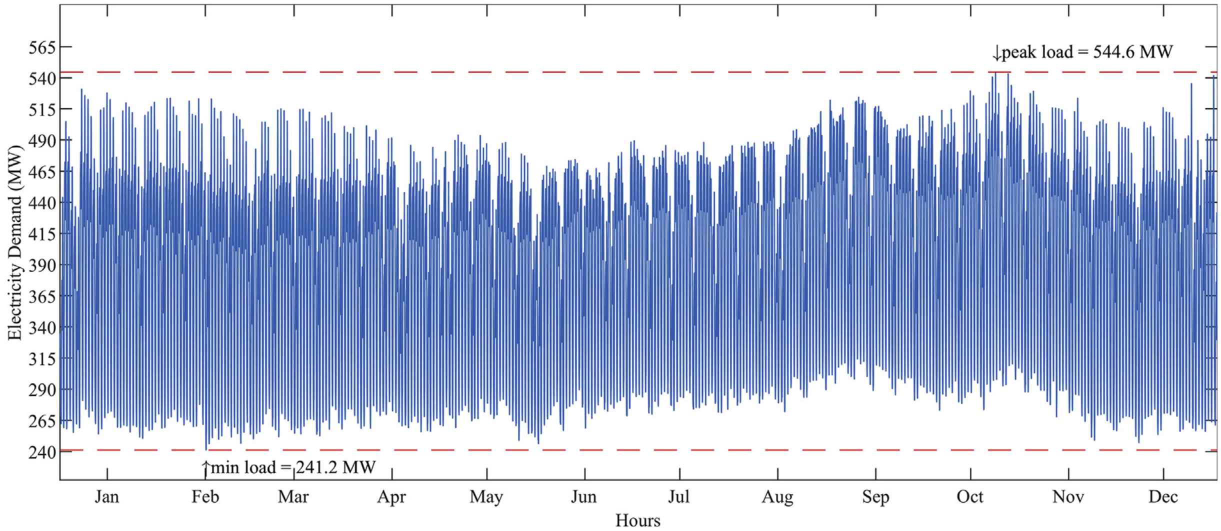

Fig. 8. Hourly average electricity demand in Gran Canaria, 2014 [45].

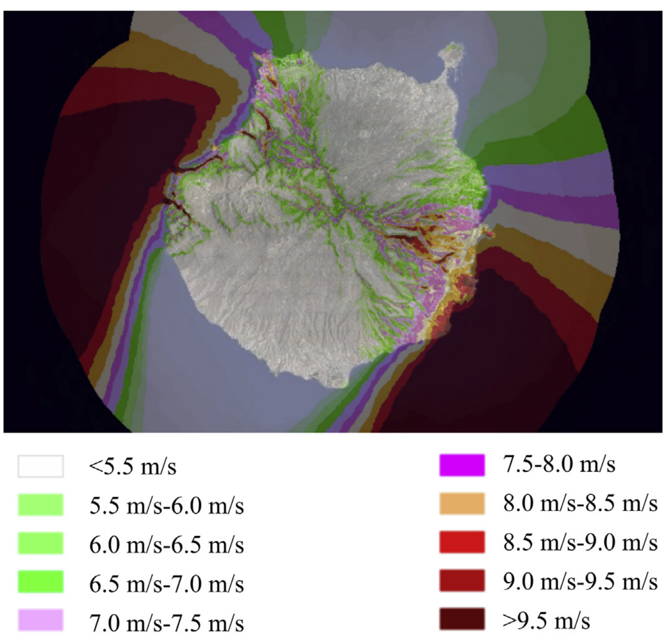

Fig. 9. Wind resource in Gran Canaria at 80 m above ground/sea level. (Source of picture: [46]).

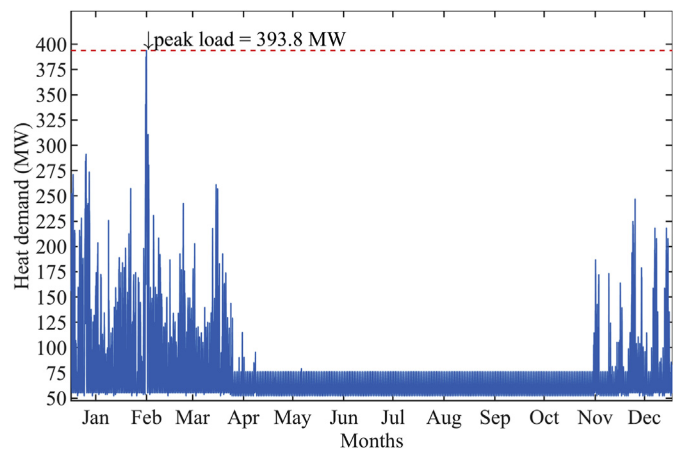

Fig. 11. Estimated mean hourly heat demand for Gran Canaria, 2014.

represents 83.5% of the total fuel consumption of the group, and natural gas (0.184 TWh). Likewise, the hotel sector is the major consumer of cooling, representing 11.5% of total electricity demand (0.39 TWh in 2014).

Half of the total water demand of Gran Canaria (51%) is supplied

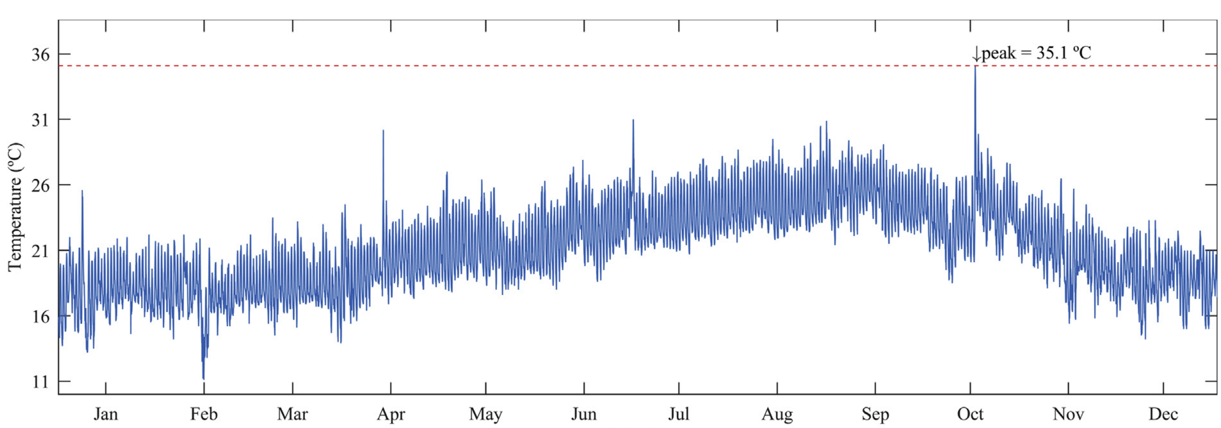

Fig. 10. Mean hourly temperature in Gran Canaria, 2014.

through seawater desalination [48]. Currently, approximately 97% of the fresh water produced via desalination is obtained using reverse osmosis technology from seawater and brackish water. Approximately 2% of the fresh water is obtained from seawater using mechanical vapour compression technology and around 1% from brackish water using the electrodialysis reversal system. Therefore, electricity is also the main driver of the island's water supply. Electricity consumption for desalination, with a high flexibility potential [49,50], represents approximately 10% of total electricity demand [48].

Overall, the most notable conclusions that can be drawn from the analysis of the current energy system of Gran Canaria, taking into account the particularities of the different agents involved and with a special focus on the unexploited flexibility potential of each sector, are as follows:

- Heating demand in Gran Canaria is almost totally supplied by fossil fuels (44.7%) and individual electric heating (27.9%). Meanwhile, just 8.9% is supplied by solar heating and there is no district heating system in the island.
- The high electricity consumption destined for cooling (11.5% of total electricity demand), the lack of district cooling systems and the particular characteristics of the island (with the highest consumption rate in summer, a time when the availability of renewable resources is similarly high), suggest that this is an area that requires special attention when considering the integration of renewables in the energy system of Gran Canaria.
- The transport sector is completely dependent on oil. However, given that the number of vehicles in use in Gran Canaria is very high [43] and given the greater efficiency of electric vehicles, it is assumed that the transition from fossil-fuelled to electric vehicles (eV) in the transport sector is potentially beneficial.
- A considerable percentage of the electricity demand is for water desalination (51%), fundamentally using reverse osmosis processes which have a high flexibility potential [50,51] that could allow the implementation of smart strategies to adapt this electricity demand to the intermittent nature of renewable energy generation.
- With 517 people/km^2 [43], the population density of Gran Canaria is high. In a hypothetical comparison with countries, Gran Canaria occupies the 22nd position worldwide, after San Marino (537 people/km^2) and just below South Korea (499 people/km^2) [52]. Moreover, the high number of tourists who visit the island and the large resulting energy consumption presume a high production of waste and, therefore, a high biomass exploitation potential.

3.2. Validation of the reference energy system model

As starting point of this study (step 1), the 2014 real energy system of Gran Canaria was used as reference scenario. As discussed in previous sections, this energy system was defined with the electricity, heating, road transport, desalination and cooling data obtained from official reports published by various institutions in the Canary Islands (Spain). Use was made, more specifically, of the annual energy report [24] and future projections [53] published by the Canary Government, statistical data published by the Canary Islands Institute of Statistics [43], a pilot project on the characterization of energy uses for the different kinds of consumer in the Canary Islands [47], data on the water system of Gran Canaria published by the Gran Canaria Island Water Authority [48] and data on the electric system published by the transmission system operator (TSO) of Spain [45]. In this first step, the reference scenario was evaluated to validate the behaviour of the model and to check whether the results obtained from EnergyPLAN are sufficiently close to the real data published by the institutions.

3.3. General procedure applied to evaluate the proposed strategies in each sector

After the validation analysis described in the previous subsection, several smart strategies within the different sectors of the energy system are proposed with a view to increasing renewable energy integration in Gran Canaria. Each strategy is applied step-by-step and evaluated following the same procedure. Firstly, a new EnergyPLAN model (scenario) is created. Secondly, the levels of the wind and PV power capacities installed in the system are modified until the optimal wind/PV configuration is obtained. Within each sector that is analysed the strategy is chosen that obtains the best results in terms of renewable penetration and system balance, and the resulting optimal scenario is then used as the starting point for the next step (sector).

In each scenario, the power capacity of each of these two types of renewable energy is varied from its 2014 value (89.5 MW for wind and 39.4 MW for PV) 10 times in equal increments until it reaches a value (1398 MW in the case of wind and 2354 MW in the case of PV) that sees production satisfying total electricity demand. When calculating the PV and wind power capacities needed for the different scenarios, the profiles of hourly distributions are considered as in the analysis of the reference scenario.

The higher the wind and PV power capacities, the greater the possibility of an electricity surplus. This energy surplus is defined as excess electricity production (EEP) [1]. Because the electricity system of Gran Canaria is an isolated system, it is assumed that the EEP cannot be exported outside the island, hence there is no income from exported electricity when EEP occurs. On the other hand, if power plant generation were to be completely avoided, there would be a lack of energy when wind and solar conditions are insufficient to meet demand. It would then be necessary either to import energy or to produce it from fossil fuels. These reasons motivated the proposal of the general procedure applied to find the optimal renewable configuration in each scenario (Fig. 4). The procedure was designed to determine the minimum intersection point of imports (fossil fuel energy needs) and exports (EEP) in each scenario. The ‘imports’ represent the energy demanded by the energy system that renewable sources are unable to cover. The ‘exports’ represent the energy that is generated by renewable sources but that the system is unable to assimilate because of insufficient demand at the moment of production of that energy. In a balanced energy system with low renewable participation, imports and exports are equal and null. However, when renewable participation increases, the highly intermittent nature of these sources results in an imbalance in relation to demand. Normally, when an energy system is interconnected with other similar systems (national European systems, for example), this imbalance is covered by energy imports or exports from/to neighbouring systems. In the case of island systems, this cannot be done because of the absence of interconnections. Nonetheless, the import/export values obtained serve as a reference to define system optimality. In this paper, the optimal configuration is considered to be that which obtains import/export values that are equal and as close to zero as possible. Each new model is executed 121 times because the renewable power capacities of both wind and PV are varied 10 times each in an iterative and sequential loop. Thus, the whole range of possible combinations of wind/PV power capacities is covered. The resulting amount of executions motivated the implementation of a set of MATLAB functions to manage this process automatically [54]: executing each simulation, analysing the results obtained from EnergyPLAN and finding the values of wind/

PV power capacities with the minimum value of import and exports for each analysed model.[1]

In all analysed scenarios, an extra generation of electric energy was considered to ensure the stability and security of the electrical power system. This stability is guaranteed by ancillary services, which include reserve power for balancing supply and demand in the short term, rotating inertia to stabilise the frequency in the very short term, synchronising torque to keep all generators rotating at the same frequency, voltage support through reactive power provision, short circuit current to trip protection devices during a fault, and the ability to restart the system in the event of a total system blackout [55]. Since the aim of this study is not solely focused on the electric sector, it has not analysed the possible reconfiguration of the electric grid to assimilate all renewable generation calculated. However, such a reconfiguration would be necessary and, therefore, as a future work, a much more detailed analysis in this respect to determine the best power system configuration for assimilation of all the proposed renewable energy generation would be an indispensable requirement. Nonetheless, the study developed in the present paper analyses the problem of renewable integration from a planning point of view and in this respect considers other studies [55] in the assumption that current technology allows the use of equipment such as synchronous compensators (SCs), which are essentially synchronous generators without a prime mover to provide active power [55]. With them, it is possible to serve the needs of all ancillary services of conventional generators except those requiring active power, i.e. they can provide fault current, inertia and voltage support just like a synchronous generator [55]. Active power is then provided by renewable generators and storage devices [55].

3.4. Smart renewable energy alternatives

As shown in Fig. 4, after validation of the reference scenario and the definition of the general procedure which is to be applied in each new proposed scenario, the methodology focuses on each sector of Gran Canaria's energy system. A summary of the different scenarios that are implemented and analysed is shown in Table 2:

All the analysed scenarios were executed under the hypothesis that all the captured renewable energy is integrated into the grid or, in other words and as is presently the case in the electric system in Gran Canaria, that renewable production is not limited by using some type of control.

3.4.1. Smart renewable energy strategies applied to the electricity sector

The first sector analysed is the electricity sector. In this part of the methodology, the first step is to apply the abovementioned procedure to serve 100% of electricity demand using only wind and PV energy. This is the second EnergyPLAN model (scenario) developed in this study, as shown in Fig. 4. After finding the optimal configuration of wind/PV to cover 100% of electricity demand, the third scenario is built following the proposal to include two waste-to-energy biomass plants as an innovative strategy. The design of these plants was undertaken considering the Danish Energy Agency and Energinet.dk recommendations, published in the Technology Data for Energy Plants report [56], and the waste data, obtained from studies developed by the Canary Islands Institute of Statistics (Spanish initials: ISTAC) [43] and the Canary Islands Government [57]. After analysis of this data, the total amount of energy-to-waste was sized at 2.11 TWh/year. According to the Danish Energy Agency, the net electricity efficiency of these waste-to-energy plants may be as high as 26% in 2020 [56] with total energy efficiency increasing to nearly 97%. The remaining 71% could then be used to produce heat, taking advantage of the incineration processes that take place in these systems.

The fourth scenario and strategy implemented in the electricity sector is based on the incorporation of PHES in the energy system. This incorporation was approached by analysing different hydro-pump and hydro-turbine power capacities. Both power capacities were varied from 100 MW to 500 MW in order to use a feasible system sized according to the current available technology in the market and the geographical possibilities in the island. The reservoir storage capacity was fixed at 5 GWh in accordance with the analysis developed by Bueno and Carta in 2006 [28]. In all the cases analysed and whenever a PHES system was used in the proposed alternatives, the hypothesis was considered that this system does not allow the pumping and turbining of water at the same time.

3.4.2. Smart renewable energy strategies applied to the heating/cooling sector

As a result of the analysis developed in the electricity sector, a new optimal scenario was obtained after application of the different previously defined steps. This scenario was built with the best performance configuration applied in each preceding step and serves as the starting point for the next analysis. In this section, three new strategies are implemented in the heating and cooling sector. The first of these (the fifth step of the method) considers the option of grouping all the heating and cooling demand as electric. After this approach, all the heating demand is included as a hypothetical district heating, although the cooling demand remains as electrical consumption. Finally, the last strategy applied in the heating/cooling sectors is to implement district heating and district cooling systems with the aim of serving all heating/cooling demands.

3.4.3. Smart renewable energy strategies applied to the desalination sector

A new optimal scenario, which is obtained after application of the heating/cooling strategies, is used as the starting point in this sector.

As previously discussed in section 3.1, the desalination sector is one of the most important sectors in the island of Gran Canaria. Some authors have demonstrated the flexible capacity of reverse osmosis desalination systems when sophisticated control techniques are implemented [49,50]. This part of the analysis concentrates on the effects of managing all desalination plants as flexible demand. In other words, a study is undertaken of how adaptation of all desalination plant operations to the hourly distribution of renewable energy sources may affect he renewable energy penetration.

Because the waste-to-energy plant incorporated in step 3 produces more heating than the heating demand of the energy system, consideration was then given to using the heating surplus in the following step. The aim is to use the heating surplus to produce desalinated water (using a new multi-stage flash (MSF) desalination plant) and subtract this water from the reverse osmosis system. In this way, part of the electricity demand is converted into heating demand. Finally, the last strategy applied to the desalination sector is to transfer all desalination technology from reverse osmosis to MSF. With this step, the heating demand increases notably and, for this reason, a new combined heat and power (CHP) plant was defined.

[1] This set of functions was packaged in a MATLAB Toolbox and is freely available on the EnergyPLAN website.

Table 2
Scenarios used to analyse the different proposed *Smart Renewable Energy Strategies*.

Sector	Scenarios	Description	Objetive
Electricity	1. 2014 Reference Scenario	The same configuration and operation strategy used in the actual system in 2014 is used.	EnergyPLAN model calibration and validation.
	2. RES Electricity demand	From the previous configuration used in the reference scenario, the installed power capacity of wind and solar are iteratively increased in the system.	To serve the maximum quantity of electricity demand with RES.
	3. Waste-to-energy plant	A waste-to-energy plant is added to the previous scenario to use the residual biomass of the island. Also, the RES electricity supply is increased iteratively as in scenario 2.	To serve part of electricity demand with electricity generation obtained from the waste-to-energy plant. To generate a heating that can be used in future scenarios.
	4. PHES Plant	A pumped-hydroelectric energy storage (PHES) plant is incorporated and its dimensioning is optimized. The RES electricity supply is increased iteratively as in scenario 2.	To increase the energy storage of the system to an optimal and feasible level.
Heating/ Cooling	5. Electric heating/ cooling	From the optimal scenario 4, all heating/cooling demand is converted to electric demand. The RES electricity supply is increased iteratively as in scenario 2.	To analyse whether this strategy allows the system better flexibility.
	6. District heating/ Electric cooling	From the optimal scenario 4, all heating demand is converted to district heating demand, the cooling demand is kept as electric demand. The RES electricity supply is increased iteratively as in scenario 2.	To take advantage of the heating generated by the waste-to-energy plant and to interconnect it with the district heating system.
	7. District heating/ cooling	From the optimal scenario 4, all heating/cooling demand is converted to district heating/cooling. The RES electricity supply is increased iteratively as in scenario 2.	To reduce the electricity demand.
Desalination	8. Flexible desalination	From the best scenario of the previous sector, the hourly profile of water demand is adapted to the wind power hourly profile. The RES electricity supply is increased iteratively.	To increase flexibility of the electricity demand of desalination plants installed in the system.
	9. Heat surplus (MSF)	From the best scenario of the previous sector, the heating surplus that is generated is used to produce desalinated water (using a multi-stage flash (MSF) desalination system). The RES electricity supply is increased iteratively.	To convert part of the electricity demand into heating demand.
	10. All desalination MSF	From the best scenario of the previous sector, all desalination technology is transferred from reverse osmosis to MSF. The RES electricity supply is increased iteratively.	To convert all electricity demand from desalination into heating demand.
Transport	11. eV - Dump charge	Taking the best scenario of the previous sector as starting point, all road transport is converted to electric transport. The vehicles are charged without any strategy. The RES electricity supply is increased iteratively.	To convert the maximum transport demand into electricity demand without any charging strategy.
	12. eV - Smart charge	Taking the best scenario of the previous sector as starting point, all road transport is converted to electric transport. The vehicles are charged following a smart charging approach. The RES electricity supply is increased iteratively.	To convert the maximum transport demand into electricity demand following a smart charging strategy.
	13. eV - V2G	Taking the best scenario of the previous sector as starting point, all road transport is converted to electric transport. A vehicle-to-grid approach is implemented. The RES electricity supply is increased iteratively.	To convert the maximum transport demand into electricity demand following the vehicle-to-grid concept.
Gas/electrofuel	14. Biogas/ Electrofuel	Taking the best scenario of the previous sector as starting point, all potential manure production in the island is used to produce biogas. The RES electricity supply is increased iteratively.	To use the biogas in biofuel production and to satisfy part of the gas demand with it.
	15. Gas CC - Higher efficiency	Considering the best configuration of the previous scenario, all thermal power plants are replaced by combined cycles fed with natural gas. The RES electricity supply is increased iteratively.	To increase the efficiency of power plants.
With the use of less mature technology	16. Gas CC - Flexible	A higher flexibility capacity of combined cycles is considered, taking into account the latest developments in steam turbines. The RES electricity supply is increased iteratively.	To look for better adaptability of generation to the intermittency/variability of RES.
	17. CO2 hydrogenation	CO2 capture solution is implemented to produce hydrogen. The RES electricity supply is increased iteratively.	To reduce CO2 emissions and to take advantage of any energy surplus to produce hydrogen and electrofuels which can be used as storage system and sources of supply.

3.4.4. Smart renewable energy strategies applied to the road transport sector

Using the best scenario created after evaluation of the different desalination strategies, three new scenarios were created to analyse the best transport strategy to convert a mainly fossil-fuelled road transport system into a wholly electric powered one. Following this plan, the eleventh scenario presented in the methodology changes petrol and diesel fuel consumption in road transport for the corresponding electricity demand. To make this conversion, it is assumed that electric vehicles have an efficiency of 0.62 MJ/km, while diesel and petrol vehicles on the island have average efficiencies of 1.5 MJ/km and 1.9 MJ/km, respectively [1]. The total number of vehicles and their typology were also considered, as per the data published by ISTAC in 2014 [43], as well as the average distance covered by each type of vehicle according to the fuel consumed and the corresponding efficiencies. It was estimated that the hourly distribution of transport in Gran Canaria follows the pattern shown in Fig. 12. On this basis, EnergyPLAN manages the corresponding electricity consumption as indicated in Refs. [23] and [58]. The aim is to power with electricity the same number of vehicles over the same distance driven per year and per vehicle. The first scenario analysed in this part of the study does not include a

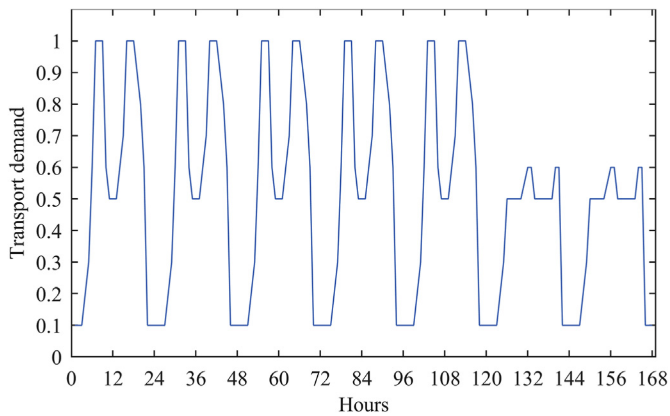

Fig. 12. Hourly transport demand considered in Gran Canaria for a week in 2014.

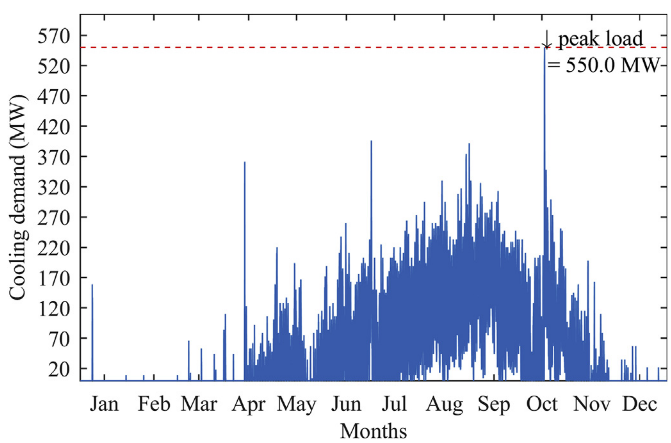

Fig. 13. Mean hourly cooling demand calculated for Gran Canaria, 2014.

smart strategy to charge/discharge the electric vehicles. This is incorporated in the following scenario (twelfth in Fig. 4), following a smart charging approach. The final scenario in the transport sector analyses the behaviour of the system if a vehicle-to-grid procedure is implemented.

3.4.5. Smart renewable energy strategies applied to the gas sector

In this section, two different strategies are applied. The first consists of subtracting organic waste from the total waste of Gran Canaria to produce biogas based on biogas methanation with hydrogen enhancement. In this scenario, the total amount of manure produced in the agricultural sector is measured and the resulting potential biogas quantified. The total amount of biogas obtained from manure and organic waste is proposed for use as electrofuel. After this step, all import needs (energy needs presently supplied by condensing power plants) of the system are instead supplied by combined-cycle power plants, following the aim of feeding the plant with gas. With this strategy, two objectives are achieved: 1) to take advantage of all the biogas production potential from organic waste and manure; and 2) to increase the efficiency of the condensing power plants to 51.9%.

3.4.6. Other potential smart renewable energy strategies that it may be possible to implement in the future

Two possible future strategies (flexible power plants and CO_2 hydrogeneration) are also proposed which (depending on the maturity of these technologies) could contribute to seeing the RES share of the PES approach 100%.

3.4.7. Scenario 2025-BAU

Finally, the BAU scenario was analysed to compare the results obtained with those expected for Gran Canaria. In accordance with the Canary Islands Energy Strategy 2015–2025 (EECan25) [53], this scenario includes onshore wind power (408.5 MW), offshore wind power (180 MW), PHES (200 MW), PV (65.62 MW), biomass (10 MW) and the proportional part calculated for Gran Canaria of electric vehicles as per the forecast in the corresponding report published by the Canary Government [53].

4. Results and discussion

Based on the method described above and case specific input data, the results for the island of Gran Canaria were calculated.

4.1. Accuracy of the reference model of the energy system of Gran Canaria

The first step of this study was to simulate the reference model of the energy system of Gran Canaria at a 1-h time resolution over the year 2014. In this section, a comparison is made between the results of this simulation and the actual data from 2014 published by several Canary Islands institutions. The energy monthly electricity demands obtained from EnergyPLAN and from the actual data gathered by official data reports are compared in Table 3. The electricity demand distribution over the year 2014 was correctly simulated. The total electricity demand obtained by EnergyPLAN for 2014 was 3379.428 GWh (see Table 4) while the actual total electricity demand was 3393.19 GWh. This small difference between the two models (0.41%) confirms the accuracy of the EnergyPLAN model.

After verifying that the electricity demand was being simulated correctly, the electricity produced from various units was

Table 3
Average monthly electricity demand obtained from the EnergyPLAN model and actual values for the year 2014 in Gran Canaria.

Month	Actual 2014 (GWh)	EnergyPLAN 2014 (GWh)	Difference (GWh)	Difference (%)
January	286.13	285.36	−0.77	−0.27%
February	257.06	256.42	−0.64	−0.25%
March	280.34	279.92	−0.42	−0.15%
April	269.59	269.25	−0.34	−0.13%
May	276.96	276.66	−0.31	−0.11%
June	270.48	269.81	−0.67	−0.25%
July	286.73	285.35	−1.37	−0.48%
August	290.36	288.52	−1.84	−0.64%
September	295.38	292.40	−2.98	−1.02%
October	303.36	300.69	−2.68	−0.89%
November	284.20	282.79	−1.40	−0.50%
December	292.60	292.26	−0.34	−0.12%
Total	3393.19	3379.42	−13.77	−0.41%

Table 4
Electricity produced for Gran Canaria in 2014 and the EnergyPLAN simulation for this data.

Production unit	2014 Production (TWh)	EnergyPLAN 2014 (TWh)	Difference (TWh)	Difference (%)
Power plants	3.114800	3.090000	−0.024800	−0.80%
Wind	0.217080	0.216968	0.000112	−0.05%
PV	0.056700	0.056695	0.000005	−0.01%

compared. As seen in Table 4, the total electricity generated from the production units is very similar in both the actual 2014 values published by Red Eléctrica de España S.A.U. (REE), Spain's TSO [45], and the results from the EnergyPLAN reference model.

Because power plant production cannot be obtained individually in EnergyPLAN, electricity production was not compared for each power plant. Instead, the annual fuel consumed by each fuel-type of power plant was compared. After seeing this comparison in Table 5, it is possible to appreciate the accuracy of the EnergyPLAN simulations. The largest difference was 1.84% for oil power-plants.

Finally, the actual RES share of Gran Canaria's PES is compared with that in EnergyPLAN. As seen in Table 5, the RES share of PES from the actual 2014 data was 1.73% and the value obtained from the reference model was 1.70%.

Once all comparisons between the reference model and the actual 2014 data had been completed and analysed, the accuracy of the model was accepted. As the largest relative difference found was just 1.82%, the reference model of the existing energy system of Gran Canaria can be used as the first step for the investigation carried out in this paper.

4.2. Smart renewable energy alternatives

In this section, the results of the proposed approach and smart renewable energy strategies operations are shown. As explained in the methods section, the same general procedure was applied to evaluate each proposed strategy in each sector. The procedure determines the minimum intersection between imports (fossil fuel energy needs) and exports (EEP) in each scenario when wind and PV are increased sequentially. The configuration which attains the minimal intersection is evaluated hourly in more detail, using the same hourly distribution profiles used in the 2014 reference scenario. This method allows measurement of the PES by fuel type to assess the impact on energy [1], on total annual CO_2 emissions [1] and on other variables such as the minimum export required in each scenario and the required wind and PV power capacities. Table 6 shows the results for each step and, specifically, the following data gathered from the EnergyPLAN output files:

- the electricity demand in each scenario
- the wind power capacity required (MW) to satisfy the resulting percentage (%) of total electricity demand
- the PV power capacity required (MW) to satisfy the resulting percentage (%) of total electricity demand
- the import/export intersection value, in TWh and in percentage (%) of total electricity demand.
- the maximum hourly import required (MW)
- the total annual carbon dioxide emissions (Mt), and
- the RES share of PES (%).

Rows 1 to 17 of Table 6 show the results obtained by the different alternatives proposed in this study. Shown in row 18 are the results obtained when simulating the 2025-BAU scenario proposed by the Canary Government [53], and in row 19 the alternative 15 proposed in the present study with electricity demand adjusted in accordance with the demand forecast for 2025.

Evolution of PES by fuel type is shown in Fig. 14, along with total annual CO_2 emissions after application of the different proposed strategies. As previously described, the implementation of each strategy in a particular sector takes into account the development made in previously analysed sectors and, therefore, the final result contains the synergies between them all. In general terms, in Fig. 14 it is possible to see how energy needs (PES) decrease as the strategies of the new sectors are incorporated. With the exception of strategy 10, in which it is proposed to produce all the water on the island with calorific power (using MSF desalination technology), all the other strategies which interrelate the different sectors reduce energy needs as well as CO_2 emissions compared to the reference scenario. Two significant changes stand out; firstly, when the island's car fleet is converted to electric vehicles (from alternative

Table 5
Total fuel consumed in Gran Canaria in 2014 and the EnergyPLAN simulation for this data.

Fuel	2014 Fuel consumption	EnergyPLAN 2014 fuel consumption	Difference	Difference
	(TWh)	(TWh)	(TWh)	(%)
Oil	15.608	15.900	0.292	1.84%
Natural gas	0.278	0.280	0.002	0.71%
Renewable	0.280	0.280	0.000	0.00%
RES share of PES	1.73%	1.70%	0.030	1.82%
Total	16.17	16.46	–	–

Table 6
Smart renewable energy results after optimization of each scenario.

	Elect. demand	PV		Wind		Import/Export		maxImport	CO2 emissions	RES share of PES
	TWh	MW	%	MW	%	TWh	%	MW	Mt	%
1. 2014 Ref. Scenario	3.4	39.5	1.7	85.9	6.5	3.09[a]	90.9[a]	527.0	4.233	1.7
2. RES Electr. demand	3.4	706.2	30.0	900.7	64.4	1.94	57.4	506.0	3.304	21.3
3. Waste-to-energy plant	3.4	470.8	20.0	826.9	59.2	1.84	54.4	467.0	3.223	28.8
4. PHES Plant	3.4	1412.4	60.0	287.0	20.5	1.60	47.3	439.0	3.025	30.5
5. Elect. heating/cooling	3.7	1533.2	60.0	329.5	21.7	1.64	44.6	500.0	3.002	31.8
6. Dis. heat/elect. cool	3.2	1100.6	50.0	380.2	29.1	1.60	50.5	400.0	2.963	29.7
7. Dis. heating/cooling	3.1	852.7	40.0	490.7	38.8	1.60	52.1	364.0	2.959	29.2
8. Flexible desalination	3.1	639.5	30.0	617.0	48.7	1.60	52.1	182.0	2.959	29.2
9. Heat surplus (MSF)	3.1	639.5	30.0	621.1	49.1	1.60	52.1	182.0	2.959	29.3
10. All des. MSF	2.5	342.2	20.0	646.1	63.6	3.22	130.7	552.0	4.953	22.2
11. eV - Dump charge	4.5	1255.4	40.0	846.5	45.4	1.79	39.7	656.0	1.760	47.9
12. eV – Smart charge	4.5	2197.0	70.0	238.6	12.8	1.60	35.4	347.0	1.596	50.1
13. eV - V2G	4.5	1883.2	60.0	423.6	22.7	1.60	35.4	523.0	1.597	50.0
14. Biogas/Electrofuel	5.5	2242.9	50.0	626.8	23.5	1.73	31.7	626.0	1.389	59.7
15. Gas CC - Higher eff	5.5	2299.8	60.0	598.5	26.3	1.42	25.7	657.0	0.494	75.9
16. Gas CC – Flexible	5.5	2299.8	60.0	640.4	28.1	0.77	14.0	721.0	0.233	87.1
17. CO2 hydrogenation	9.0	3107.4	50.0	1479.9	40.1	1.73	19.4	1096.0	0.199	91.9
18. 2025-Business-as-usual	4.4	65.6	2.3	588.5	32.4	3.27[a]	74.7	182.0	3.360	33.9
19. Alter.15 (2025-el.dem)	7.26	2519.2	50.0	823.18	27.5	1.59	21.81	657.0	0.593	74.6

[a] In scenarios 1 and 18 only the values of imports are shown (fossil fuel energy needs) as in these scenarios no search is made for an import/export intersection point.

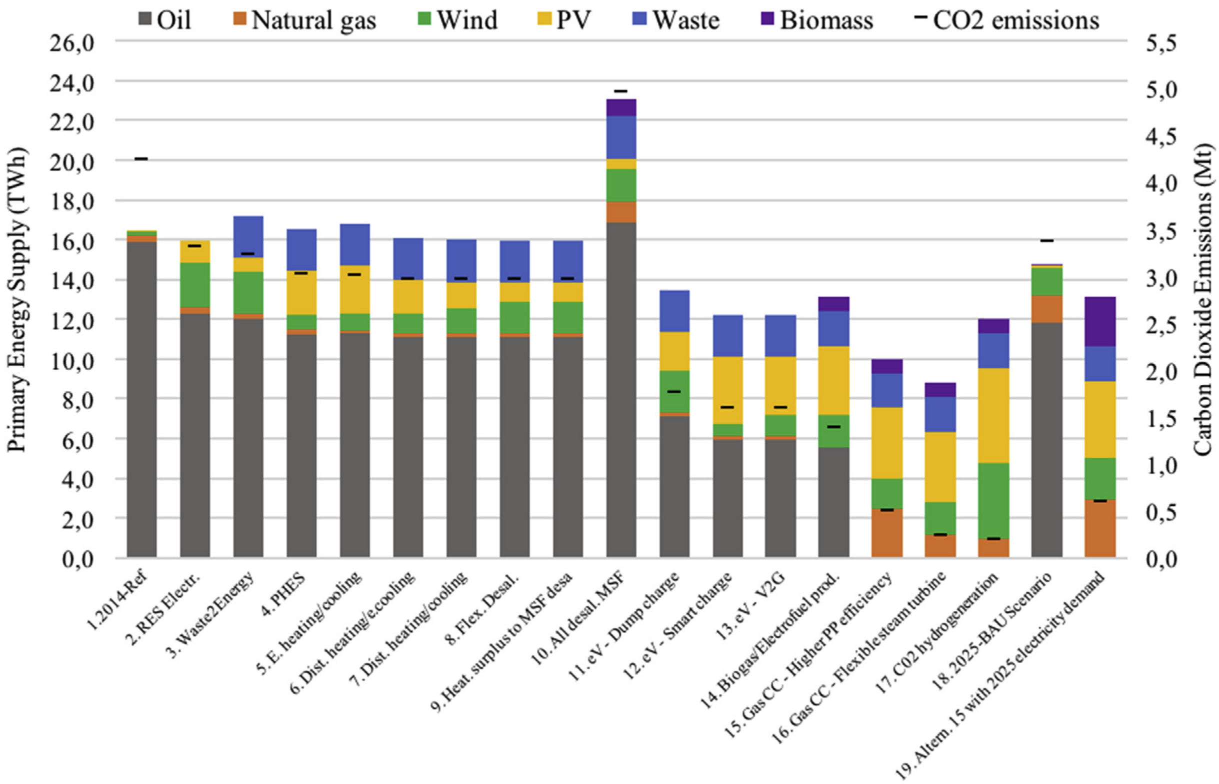

Fig. 14. Primary energy supply by fuel and carbon dioxide emissions for all smart renewable energies strategies applied to the energy system of Gran Canaria to increase the renewable energy penetration.

11 to 17), and secondly when the efficiency of the generator groups is increased (combined cycles) by using natural gas instead of gasoil as fuel. The following subsections describe in greater detail the most significant aspects of the results obtained in each sector.

4.2.1. *Smart renewable energy strategies applied in the electricity sector*

Three strategies were applied in the electricity sector. The first (scenario 2) is based on the optimal increment of wind and photovoltaic power capacities to satisfy the total electricity demand of the reference model with intermittent renewable energies. Both power capacities were varied 10 times from the actual values in 2014 to the corresponding values which satisfy total electricity demand. In the first proposed alternative (scenario 2), the PV power capacity was thus varied and tested from 39.4 MW to 2354 MW and the wind power capacity from 89.5 MW to 1398 MW. For each PV power capacity value, each wind power capacity value was executed in EnergyPLAN, obtaining 11 import/export results for each analysed PV configuration. Fig. 15 shows the sequential searching of the minimal intersection between imports and exports. The red lines of the different figures represent the imports (fossil fuel energy needs) and the blue lines represent the induced exports or EEP of each configuration. The lowest import/export intersection can be seen highlighted in Fig. 15-d. As discussed previously, the optimal criterion followed in this study is based on searching for the minimum import/export intersection values. The selected configuration (whose import/export values are equal and as close to zero as possible) guarantees a balanced energy system with the maximum renewable energy used to cover the electricity demand.

The execution of each wind/PV combination produced a total of 121 instances of imports/exports and 9 intersection points (Fig. 15). As can be seen in Fig. 15, the instances represented in Fig. 15-j did not result in intersections. All the intersection points are shown in Fig. 16, where the minimum is also highlighted.

Finally, the optimal wind/PV configuration obtained (with the minimum import/export intersection) was executed in EnergyPLAN again to obtain the results shown in the second row of Table 6. As can be seen, this step in the methodology achieved a notable increase in the RES share of PES. The low value attained in the 2014 reference model (1.70%) is increased to 21.3%.

The third scenario was built following the procedure explained in section 3.4.1 As mentioned previously, this strategy is based on the inclusion of two waste-to-energy plants. The total amount of waste-to-energy was sized at 2.11 TWh/year, of which 1.50 TWh are for district heating production, and just 0.55 TWh for electricity production. With the inclusion of waste-to-energy plants, a 28.8% RES share of PES was attained. The minimum import/export intersection was 1.84 TWh (54.36% of total electricity demand), with PV energy covering 20% of total electricity demand (470.79 MW of PV power capacity) and wind energy 59.16% (826.86 MW of wind power capacity).

The four alternatives created were based on the implementation of a new PHES system. Sizing of the PHES was carried out by testing five different power capacities in the pump/turbine systems and using the same energy storage capacity value (5 GWh). The pump and turbine power capacities were varied from 100 MW to 500 MW and the results can be seen in Table 7. A PHES power capacity of 300 MW was chosen. The small improvement achieved in the import/export intersection variable when power capacity was increased to 400 MW did not justify selection of a bigger system. After implementation of this strategy, the RES share of PES was 30.5%. The import/export intersection was reduced from the 1.84 TWh obtained in the previous strategy to 1.60 TWh. This

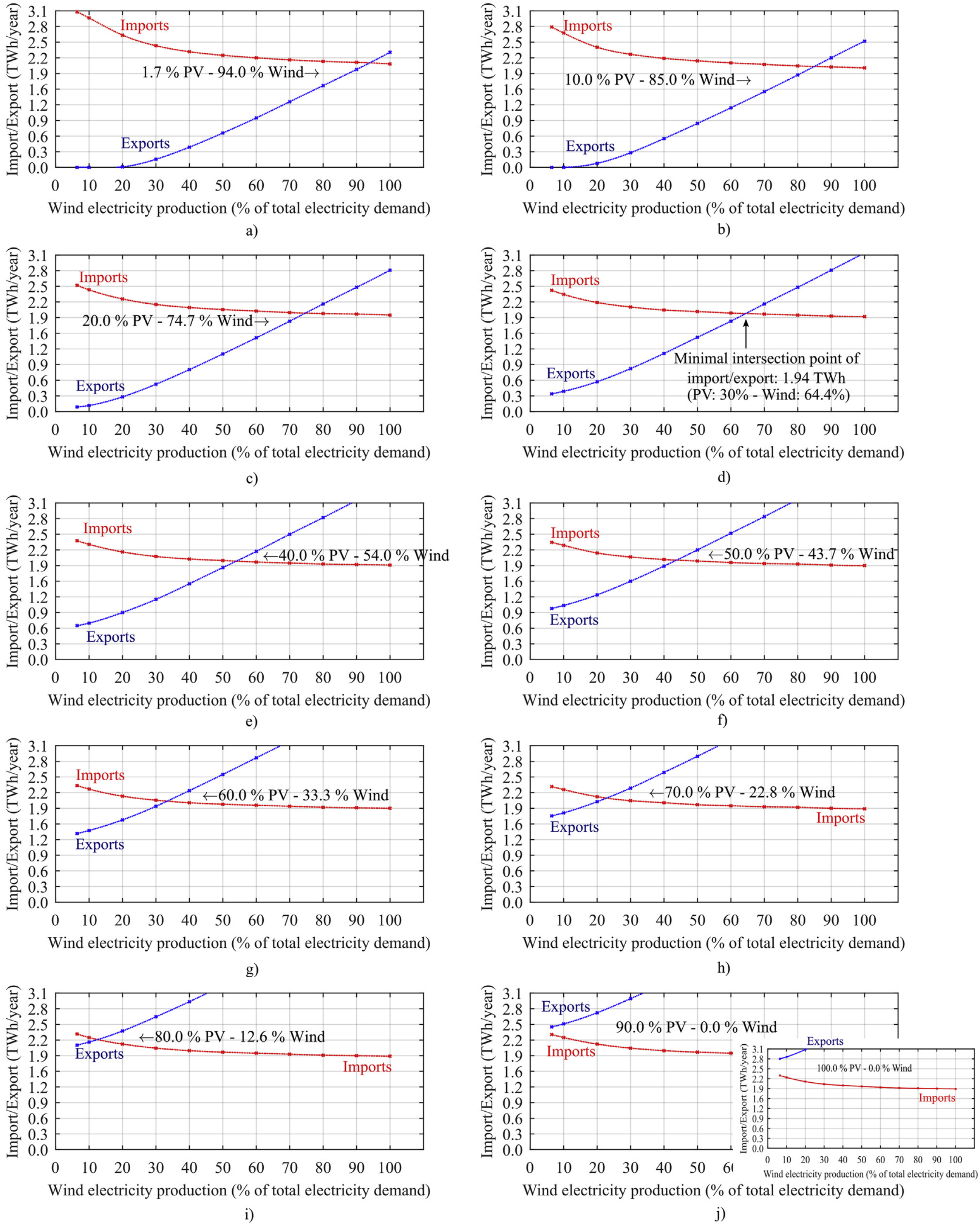

Fig. 15. Import (in red) and export (in blue) results when varying wind power capacity and PV power capacity to obtain the electricity production percentages indicated with each technology. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

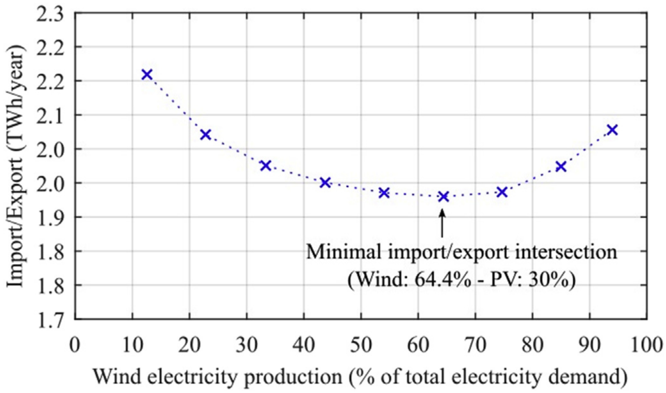

Fig. 16. Import/export intersections for each wind/PV combination. The minimum import/export intersection is highlighted.

import/export represents 47.34% of total electricity demand and 10% of PES. It was attained with 1412.4 MW of installed PV power capacity (60% of total electricity demand) and 287.0 MW of installed wind power capacity (20.5% of total electricity demand).

Inclusion of the PHES system has a significant consequence, namely that the optimization model employed inverts the trend of the results thus far obtained. An increase is observed of installed PV power at the expense of wind power (see Table 6). This is because, due to the nature of PV generation, the production peak is concentrated around the midday hours and an increase of this technology, combined with the sized PHES, produces lower energy surpluses than an increase of installed wind power. It can be seen that, once a sufficient level of installed wind power to regularly cover the trough hours of demand (night) has been attained, it is possible to reduce the energy surplus produced by the PV production peak through activation of the PHES pumping system. However, the PHES system combined with high installed wind power is not so effective because energy surpluses take place at all times of the day and their reduction is limited to the capacity of the pumping system. To illustrate this phenomenon, Fig. 17-a shows the mean annual daily profile (means of hourly powers of all the year) of electricity production generated by the technologies taking part in the optimum RES configuration chosen for alternative 4 by the optimization algorithm. This optimum configuration has 60% of installed PV power and 20.5% of installed wind power. Also, in Fig. 17-b, the hourly means are shown of a configuration rejected by the optimization algorithm which proposes use of a higher amount of wind power (1.7% of installed PV power and 80% of installed wind power). Shown in Fig. 17-c is the hourly and annual energy surplus of the two configurations.

Accordingly, it is observed in Fig. 17-a that hourly electricity production matches demand (indicated in red) during most of the day, with a surplus energy (generation greater than demand) only produced during the midday hours (higher PV production). This surplus is partly compensated for by PHES pumping and is exploited to load this storage system. In Fig. 17-b and Fig. 17-c, however, it is seen that when employing a configuration with a higher amount of installed wind power the energy surplus takes place, on average, in all the hours of the day. Consequently, in Fig. 17-c, it is seen that employing a system with a higher wind energy generation capacity than that calculated by the algorithm, results in a higher annual energy surplus.

In short, the three smart renewable energy strategies applied in the electricity sector saw RES penetration rise from 1.7% to 30.5%. Fig. 18 also shows the PES and CO_2 emissions for this step of the study. These three strategies converted the low RES share obtained in the 2014 reference scenario (1.7%) to a notably higher RES share value (30.6%) and reduced total carbon dioxide emissions from 4.23 Mt to 3.03 Mt. The inclusion of waste-to-energy plants produces a small increase in PES because they produce a heating surplus, a question which is addressed in subsequent steps. The addition of the PHES changes the RES configuration of the system and increases PV energy participation against that of wind energy.

4.2.2. Smart renewable energy strategies applied in the heating/cooling sector

After the work carried out in the electricity sector, three new strategies were implemented in the heating/cooling sector. Strategy number five (see Fig. 4, Fig. 19 and Table 6) considers all heating/cooling demand (Figs. 11 and 13, respectively) as electric demand (see Fig. 19).

With optimization of the electric RES supply configuration, this scenario obtained a 1.2% increase in the RES share of PES compared to the previous strategy. However, because the waste-to-energy plant produces 1.50 TWh of heat which is not being used, this scenario retains a large and inefficient heating surplus of 1.50 TWh. With this in mind, the sixth strategy in the heating/cooling sector was implemented. This smart renewable energy strategy moves all heating demand to a district heating system and retains all cooling as electric demand. However, a heating surplus remains and, therefore, the cooling demand is also converted to district cooling in alternative 7.

After application of smart renewable energy strategies in the heating/cooling sector the RES share of PES is slightly reduced but, on the other hand, the whole energy system is more balanced. With this step of the methodology, the production of heating from the waste-to-energy plant is used to meet the heating/cooling demand. As no hourly consumption data are available, the hourly distributions for this sector were estimated using real temperature data and annual fuel consumption data obtained from official reports published by public administrations of the island [24,47].

4.2.3. Smart renewable energy strategies applied in the desalination sector

Three desalination strategies were applied to analyse the contribution of this sector to renewable energy penetration into the energy system (see Fig. 20). Practically all the desalination plants on the island of Gran Canaria are based on reverse osmosis technology

Table 7
Procedure of sizing and PHES power capacity selection.

	Turbines/Pumps Power Capacity	PV		Wind		Import/Export		CO2 emissions	RES share of PES
	MW	MW	%	MW	%	TWh	%	Mt	%
4a. PHES	100	706.2	30	702.8	50.3	1.69	49.96	3.094	29.8
4b. PHES	200	1177.0	50	427.1	30.6	1.64	48.33	3.053	30.3
4c. PHES	300	1412.4	60	287.0	20.5	1.60	47.34	3.025	30.5
4d. PHES	400	1647.8	70	150.4	10.8	1.61	47.36	3.019	30.6
4e. PHES	500	1647.8	70	150.8	10.8	1.62	47.65	3.017	30.6

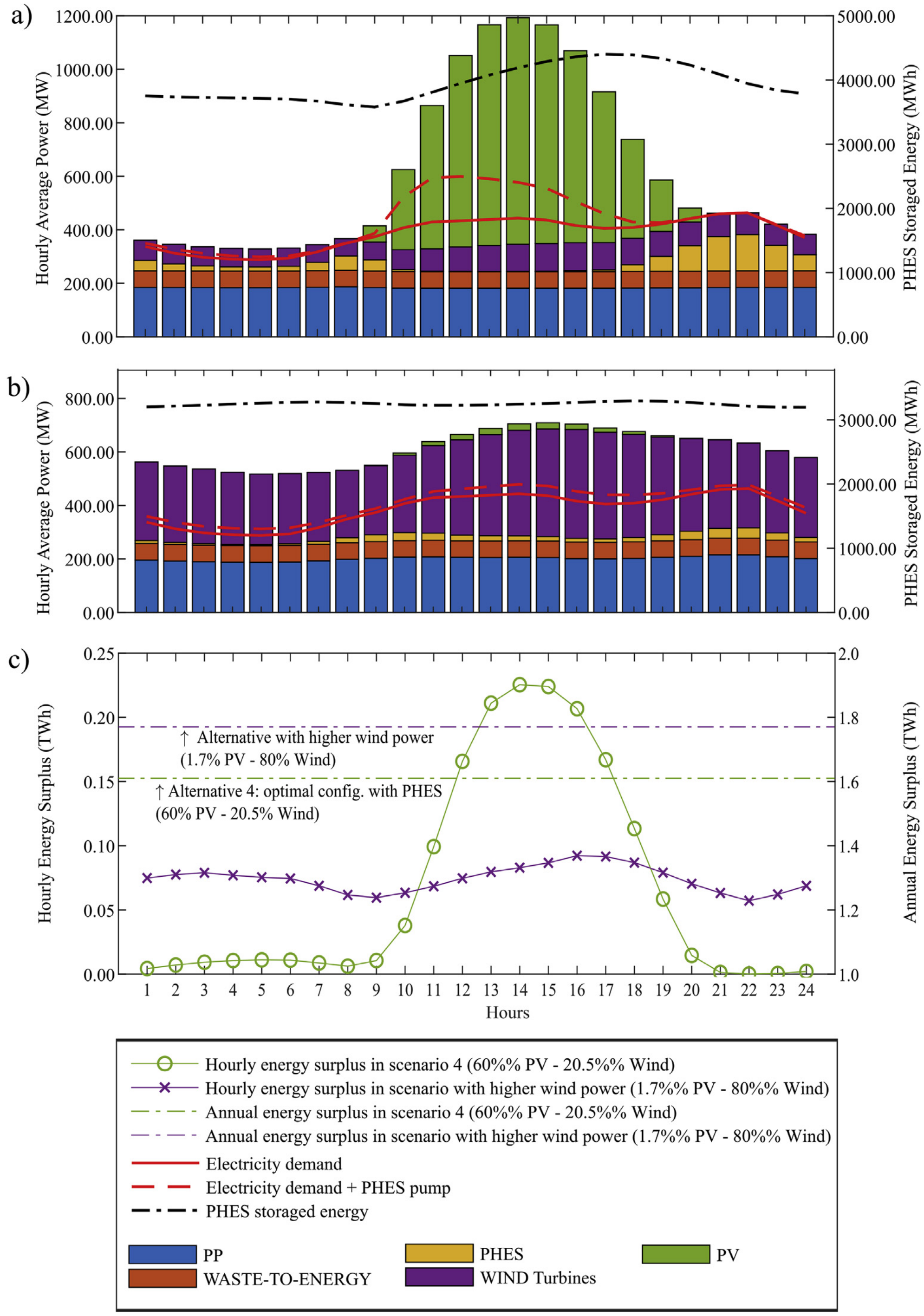

Fig. 17. a) Diurnal pattern of the mean electric powers by technology corresponding to the whole year under consideration and the optimum configuration chosen by the optimization algorithm (demand covered by 60% of installed PV power and 20.5% of installed wind power). a) Diurnal pattern of the mean wind powers by technology corresponding to the whole year under consideration and a configuration rejected by the optimization algorithm with more installed wind power (demand covered by 1.7% of installed PV power and 80% of installed wind power). c) Hourly and annual energy surpluses of both configurations.

[48]. Given the high flexibility potential of this technology [49,50], the first strategy is based on adapting all desalination power plant operations to wind energy distribution. For this purpose, it was considered that water demand could be adapted to wind distribution following a 24-h moving average of the hourly wind production distribution. A minimum desalination plant operating rate was respected. In 2014, overall desalination plant efficiency was 4.9 kWh/m^3, with a desalinated water volume for Gran Canaria of 72.8 hm^3 and a corresponding electricity demand of 0.36 TWh [48]. The application of this strategy does not contribute notably to a RES share increment because flexible desalination management of desalination should be accompanied by flexible power plant management. In this part of the study, the lack of flexibility of the power plants considered for electricity production (high technical minimum power production values) does not allow advantage to be taken of improvements as a result of desalination flexibility.

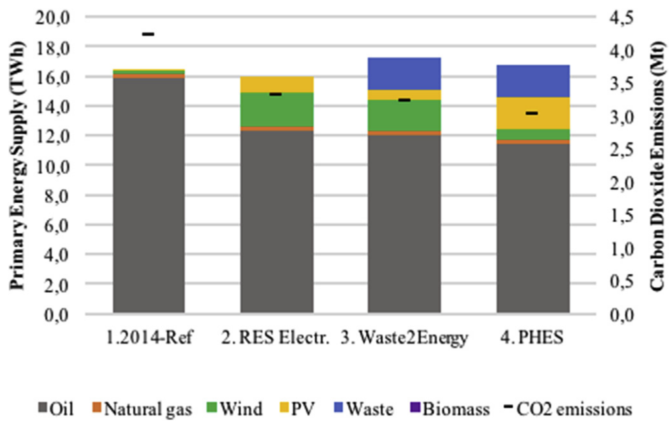

Fig. 18. Primary energy supply by fuel and carbon dioxide emissions for the reference 2014 scenario and for the three smart renewable energy strategies applied in the electricity sector.

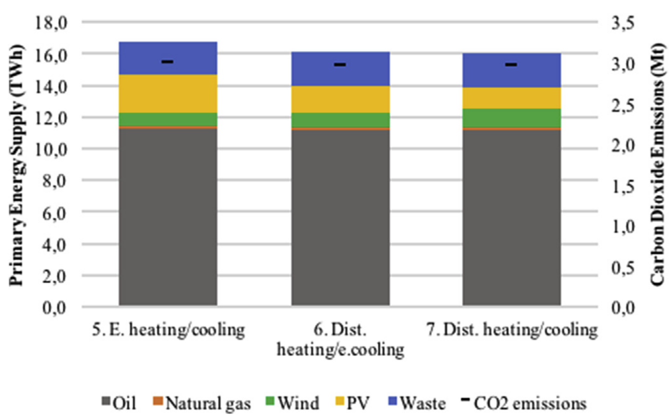

Fig. 19. Primary energy supply by fuel and carbon dioxide emissions for the three smart renewable energy strategies applied in the heating/cooling sector.

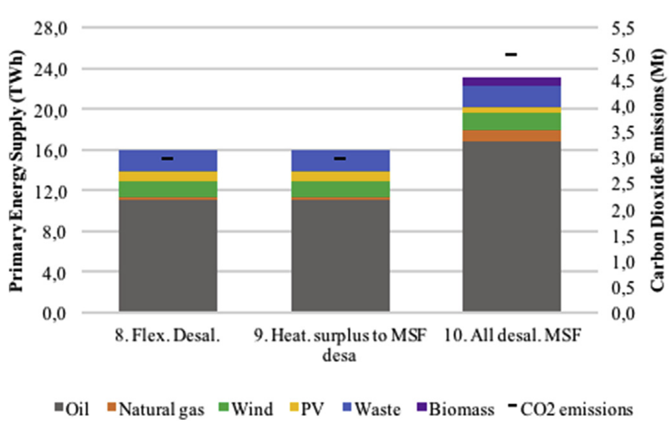

Fig. 20. Primary energy supply by fuel and carbon dioxide emissions for the three smart renewable energy strategies applied in the desalination sector.

Nevertheless, as can be seen in Table 6, flexibility in the desalination sector reduces particularly the maximum import needs of the energy system and this fact is very favourable. In this respect, it would be necessary to explore in a future work adaptation of desalination to renewable generation with different hourly patterns to the one used in this study, as well as the use of other strategies such as the accumulation of water in periods of energy surpluses for its use in periods with low renewable energy resources.

The second strategy implemented in this sector takes advantage of the small surplus remaining in the heating sector to produce water using MSF technology and proportionally reduce the electric consumption of reverse osmosis. To make this change, a thermal energy consumption of 190 MJ/m^3 was considered for MSF technology [59]. However, the lower efficiency of MSF does not allow the generation of major benefits in the system and, for this reason, the implementation of this kind of desalination is not recommended.

Finally, to analyse an extreme scenario all water desalination production was converted to MSF technology (scenario 10). In this case, production of the 72.8 hm^3 of water demand on the island was considered using this technology powered by heating. However, the energy requirements of this technology involve the need for new CHP plants to produce additional heating. This significantly increases the PES and the fossil fuel dependency of the energy system. It is seen that the increase in heating demand does not compensate the loss of efficiency of this technology vs. the use of reverse osmosis and, given that demand is reduced in the electric sector, less PV and wind energy is also integrated.

Therefore, of the three strategies implemented in the desalination sector, the first was chosen to continue with development of the system.

4.2.4. Smart renewable energy strategies applied in the transport sector

The strategies developed in the transport sector introduce a very high improvement from the point of view of the renewable energy system (see Fig. 14).

The introduction of electric vehicles reduces the PES of the energy system from around 16 TWh to 13.5 TWh, principally because electric vehicles are more efficient than petrol and diesel vehicles [1]. However, it is also possible to take advantage of the batteries in electric vehicles to improve flexibility in the energy system. With an appropriate charging/discharging strategy, electric vehicles enable more wind power to be integrated and thus replace fossil fuels in the power plants (see Fig. 21). EnergyPLAN allows two strategies to be implemented: the first is called smart charging and consists of charging electric vehicles when intermittent renewable energy sources have a high level of electricity production. The second strategy is based on the Vehicle-to-Grid (V2G) concept and comprises the management of vehicle charge and discharge processes to adapt them to the intermittent renewable energy sources

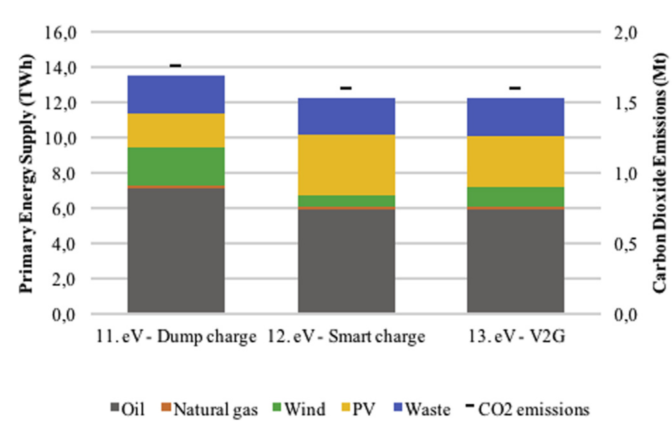

Fig. 21. Primary energy supply by fuel and carbon dioxide emissions for the three smart renewable energy strategies applied in the transport sector.

state.

With incorporation and management of the electric vehicle, the use of PV energy is increased at the expense of wind energy. Introduction of the electric vehicle and application of the smart charging strategy [58] allows management of the charging of these vehicles in such a way that peak demand coincides with renewable production peaks. A comparison is shown in Fig. 22 between the optimum configuration chosen by the optimization algorithm for scenario 12 (eV-Smart charging) and another configuration rejected by the optimization algorithm but with a higher installed wind power. It can be seen in Fig. 22-a that, when the option is taken of a configuration which employs higher installed PV power and part of

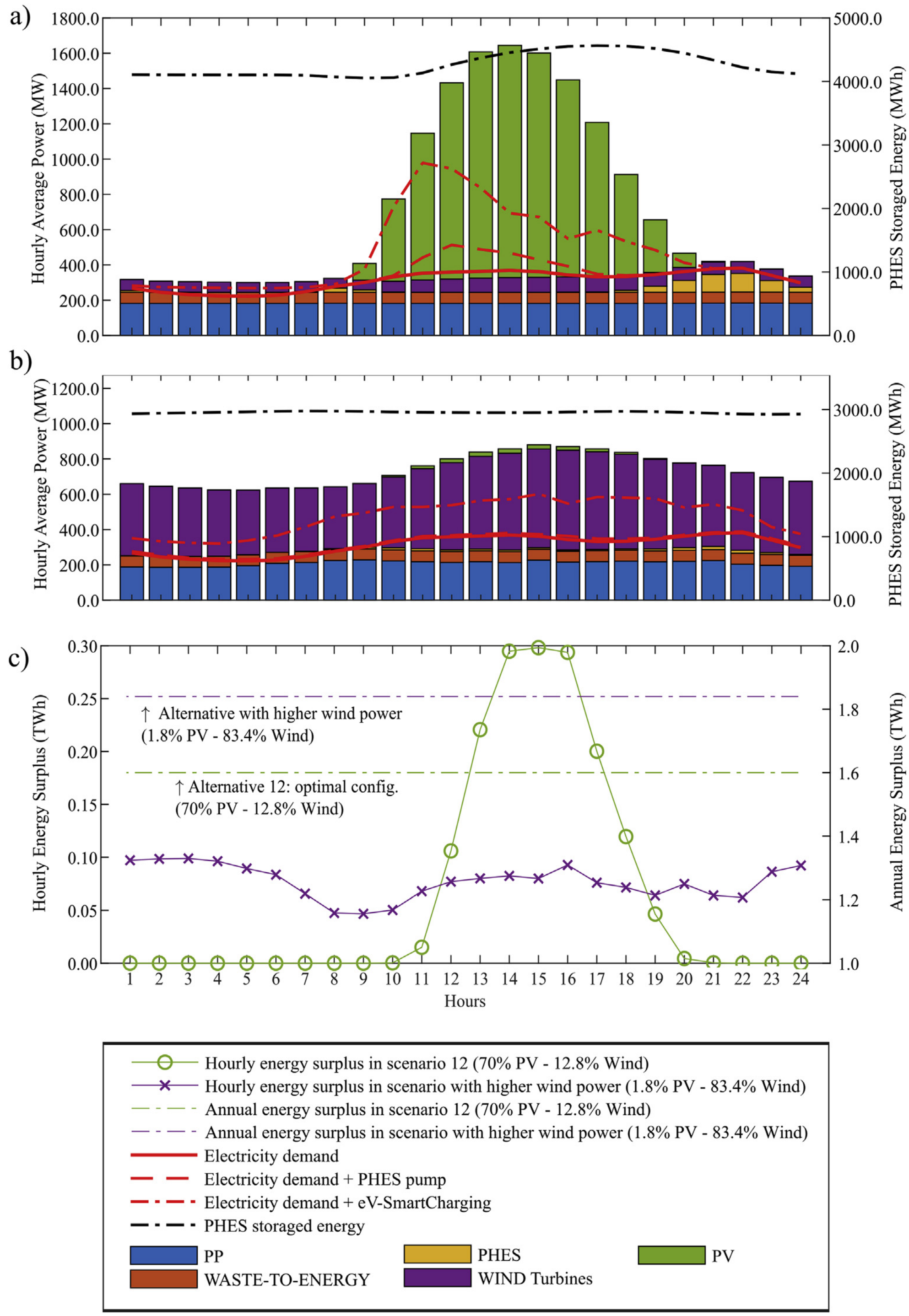

Fig. 22. a) Diurnal pattern of mean electric powers by technology corresponding to the whole year under consideration and the optimum configuration chosen by the optimization algorithm when the electric vehicle is used with the smart-charging strategy (demand covered by 70% of installed PV power and 12.6% of installed wind power). a) Diurnal pattern of the mean electric powers by technology corresponding to the whole year under consideration and a configuration rejected by the optimization algorithm with more installed wind power when the electric vehicle is used with the smart-charging strategy (demand covered by 1.8% of installed PV power and 83.4% of installed wind power). c) Hourly and annual energy surpluses of both configurations.

the charging of electric vehicles is shifted to the middle hours of the day (10:00–14:00), fewer energy surpluses are produced (Fig. 22-c) than when vehicle charging is more evenly distributed throughout the day but a higher amount of installed wind power is used (Fig. 22-c). During these hours, approximately half of the vehicles are not in use, and there is a higher PV production that is compensated in this way.

4.2.5. Smart renewable energy strategies applied in the gas sector

The first strategy applied in the gas sector (alternative 14) was based on the use of organic waste for biogas and electrofuel production. This strrategy increased the RES share of the PES of Gran Canaria to 59.7% while reducing CO_2 emissions to 1.39 Mt. However, the application of the second strategy (alternative 15) in this sector was especially remarkable. When the supply of all energy needs was met by combined cycle power plants instead of condensing power plants and these plants were fed with gas, the efficiency of the power plants increased considerably (to 51.9% from 31.7%) and, as a result, the RES share of PES rose sharply (to 75.9%) while CO_2 emissions were reduced to 0.494 Mt. This strategy succeeds in suppressing the oil dependence of the energy system as, after its application, renewable penetration was increased by 16.2% with respect to the alternative (14) previously implemented (see Fig. 23).

4.2.6. Other potential smart renewable energy strategies that will be able to be implemented in the future

So far, the application of the proposed strategies has achieved a scenario with a 75.9% RES share in the PES of Gran Canaria. Nonetheless, if the flexibility of steam turbines (used in combined cycle power plants) is improved, and the technology of CO_2 hydrogeneration [60] matures, the renewable energy penetration in the energy system of the island could be significantly increased. The application of these two technologies could obtain a future scenario with a 91.9% RES share in the energy system of Gran Canaria.

Technological improvement of steam turbines would raise renewable integration considerably (see Fig. 14 and 24). Only the reduction of the technical minimum electricity production value for combined cycles allowed an increase of 11.2% in the RES share of the PES of the system (alternative 16) compared to the previously analysed alternative (alternative 15) (see Fig. 24). With the incorporation of the technology of CO_2 hydrogeneration a further 4.8% increase was obtained.

After implementation of all the renewable energy strategies, the results indicate that renewable penetration in the energy system increases while both PES and CO_2 emissions are reduced (see

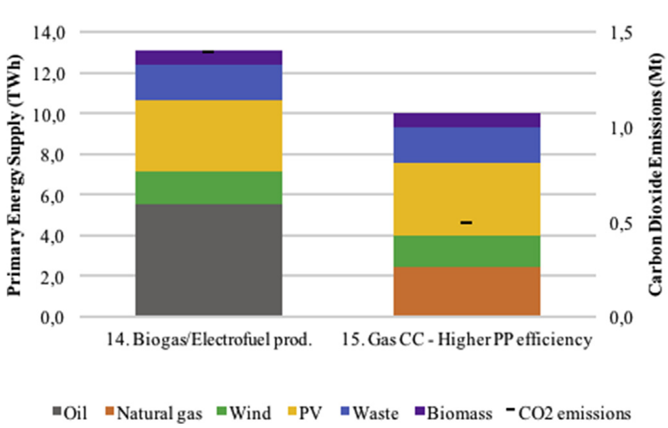

Fig. 23. Primary energy supply by fuel and carbon dioxide emissions for the two smart renewable energy strategies applied in the gas sector.

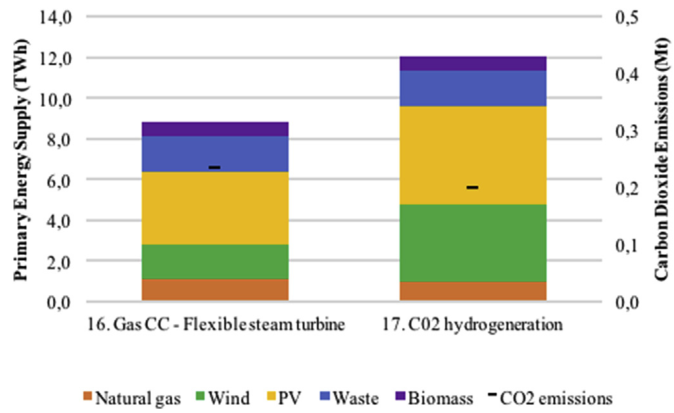

Fig. 24. Primary energy supply by fuel and carbon dioxide emissions for two of the future smart renewable energy strategies proposed.

Fig. 14). The maximum RES share achieved is 91.9% in alternative 17, and the minimum CO_2 emissions are approximately 0.2 Mt. To obtain these results, the proposed method estimates wind and PV power values which differ substantially from the actual amounts presently installed. As can be seen in Table 6, the maximum powers suggested are obtained for the final proposed scenario, which would only be carried out if the technology acquires sufficient maturity for its implementation. The results of this scenario estimate an installed wind capacity of 1479.9 MW and an installed PV capacity of 3107.4 MW. It should be noted that the technical feasibility of installing these maximum capacities for Gran Canaria has been reported in various scientific studies [25,26,61]. In Ref. [26], the techno-economical wind potential of some islands including Gran Canaria is evaluated. The authors of that study report that the installable onshore wind power of Gran Canaria is 896 MW, if all the technical, economic and territorial restrictions are considered, including the slope of the terrain. According to these authors [26], if such restrictions were not considered the installable power would rise to 1320 MW. In Ref. [61], an analysis is undertaken of the offshore wind potential of the island, and it is concluded that an installable wind power capacity of 332 MW (with foundation fixed at the bottom of the sea) or 1510 MW (with floating foundation) is feasible. Therefore, if the sum of these amounts is considered, the technical feasibility of the wind powers proposed in the present analysis is seen to be viable. Likewise, prior to the present study, it was estimated in Ref. [25] that the available roof surface for solar installations on the island amounts to 13.1 km^2 if the available roof area shares its surface between energy uses (for both solar thermal and PV) and other purposes not related to energy production. In that study, a surface/power ratio of 7 m^2/kWp was used, averaging the values calculated in four prior works referenced in Ref. [25]. Therefore, up to 1.87 GWp of PV solar power could be installed in the most unfavourable scenario described in that study. In this way, an additional 8.68 km^2 roof surface area would be required to attain the 3.11 GWp calculated for the most ambitious scenario proposed in the present study, a reasonable value when considering that this represents just 0.56% of the whole island.

All the wind turbines installed in 2014 are found in the designated geographic areas (Fig. 3) included in the territorial development plan drawn up the Gran Canaria Island Government for the installation of future wind farms [62]. The procedure followed by EnergyPLAN of estimating the wind and PV power productions involves hourly extrapolation of the recorded powers. Firstly, these hourly distributions are normalised and, if the installed power is increased, the power produced in each hour is proportionally increased. This implies that this procedure is valid for the case study, as the form of the power distributions and the geographical area for the location of RESs are closely related.

4.2.7. Comparison of the results obtained for the 2025-business-as-usual scenario with the proposed alternatives

After simulating the BAU scenario proposed by the Canary Government for 2025 [53], it is possible to appreciate the importance of carrying out an adequate planning study to integrate the largest amount of RES possible. Although for this scenario a significant increase of RES in the system is proposed, this is undertaken without exploiting the synergies of the different sectors or the use of any technical criterion of optimization as is proposed in the present study adapted to the energy system under evaluation. As was shown in sections 4.2.1 and 4.2.4, according to the present study, enabling management of part of the demand (incorporating a PHES system or transferring the fuel-based vehicle to a manageable electric vehicle) rewards the installation of PV energy, and this should be taken into account when planning the future energy system. The level of the RES share of PES attained by this BAU scenario is significant (33.9%) but falls short of the results obtained with various of the alternatives proposed in the present study. According to the demand projections of the Canary Government for 2025, there will be an increase in annual electricity consumption of 44.4%. Therefore, with the aim of appropriately comparing the results of the 2025-BAU scenario, this increase in electricity demand was introduced into the proposed alternative 15 and the previously explained method was executed again. As can be observed in Fig. 25 with the selected method, a RES share of 74.6% of the PES is obtained in comparison with the 33.9% attained by the BAU scenario. To be more precise, the method used optimized the energy system in such a way that, in 2025, 2.90 TWh of energy is provided by natural gas, 2.08 TWh by wind, 3.92 TWh by PV, 1.76 TWh by waste and 2.48 TWh by biomass.

It is important to highlight the difference between the final results obtained in the present study and the results after application of electricity sector-based strategies (which have to date been the usual strategies implemented in published studies). In this sense, in this article the positive effects are demonstrated of combining the synergies, the flexibility potential and the energy storage capacity of all sectors involved in the energy system. In this way, the PES of Gran Canaria is reduced from the 16.46 TWh/year of the initial scenario (alternative 1) to an estimated 10.02 TWh/year for the proposed alternative 15. Focusing only on the electricity sector, the maximum RES penetration in the energy system is 30.5% as opposed to 75.9% when combining all mature technologies of all the sectors involved in the system. It can therefore be concluded that interconnection of all the energy sectors in the manner proposed in the present study is a more appropriate solution to the problem of increasing renewable penetration than focussing on a single sector, which has been the case in the vast majority of previously published studies for other islands. At this point, a special mention needs to be given to the extreme difficulty of comparing the results obtained in the present study with those from other previously published studies. Firstly, as stated in the Introduction section, only three studies have been conducted on better renewable penetration in the energy system of Gran Canaria. None of these have considered all the sectors participating in the energy system, but instead have concentrated their attention solely on the island's electricity sector, proposing and technically validating the solution of incorporating a pump-hydro-power plant [28,29,31]. These studies show that renewable energy penetration in the island is indeed improved with this solution. However, the present paper goes considerably further than considering only the energy sector and proposes a multitude of additional scenarios to achieve the goal of increasing renewable penetration. Another study, which could serve as a comparative reference in that it contemplates the energy system of Gran Canaria island, is that undertaken by Gils and Simon [20]. However, as previously mentioned, this study considers interconnection between the different islands of the Canary archipelago via submarine power transmission lines and, therefore, its field of application, methodology and the scenarios implemented make the results of that particular study extremely difficult to compare with those obtained in the study described in the present paper.

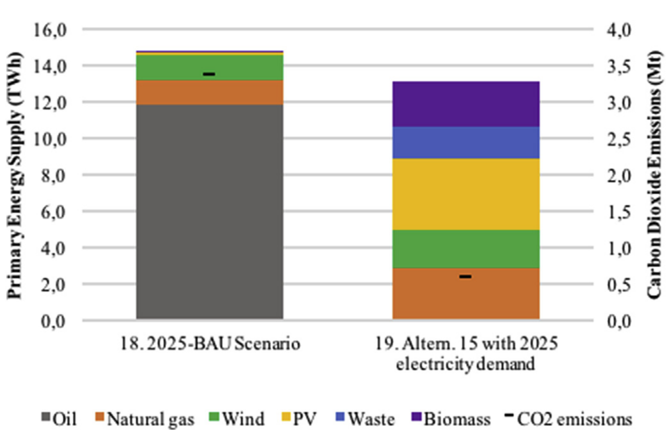

Fig. 25. Primary energy supply by fuel and carbon dioxide emissions for the 2025-BAU scenario in comparison with alternative 15 with electricity demand accordingly modified.

5. Conclusions

In this study, a new method is presented which uses the Smart Energy Systems concept to increase the share of renewable energy penetration on islands. The method is applied to the island of Gran Canaria (Spain) in a series of 17 steps in which all the energy sectors are integrated, converting the energy system of this island from being primarily fossil fuel-based to a nearly 100% renewable energy system.

The study shows that interrelating the different sectors reduces considerably the energy needs of Gran Canaria, significantly lowering its primary energy supply.

The results indicate that the proposed technical analysis could obtain a 75.9% renewable energy system, using technologies and strategies that are already mature enough to be implemented at the present time (alternative 15).

It was detected with the proposed optimization method that, for the case study, if demand flexibility is increased and part of the demand can be transferred to other hours in the day (through the use of a PHES system, for example, or smart-charging of electric vehicles), it is preferable to increase the installed PV power as lower energy surpluses are incurred than if the installed wind power capacity is increased. To further investigate the applicability of any of the proposed alternatives, an additional study considering the costs of each alternative would be required. However, the present study could be considered the first step towards achieving a future 100% renewable energy system for Gran Canaria, describing for the first time the potential of cross-sectoral interconnection on one specific island. The individual potential of each sector involved in the energy system is also quantified and, for the first time, an analysis is made of the potential contribution of each sector to improve RES integration in the energy system of the island. Therefore, it can justifiably be argued that this work can serve as a roadmap for future planners of scenarios that aim for a higher participation of renewable energies in stand-alone energy systems and as a starting point for more detailed analyses in the different sectors considered.

Acknowledgements

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