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The role of H_2 in the decarbonization of isolated electrical systems: challenges in the mobility

B. González-Díaz[1], L. Rodríguez-Urrego[1], A. Barroso-Alonso[1], N. Martín-Dorta[2], E. González-Díaz[2] and Francisco Ramos-Real[3].

[1] Departamento de Ingeniería Industrial, Escuela Superior de Ingeniería y Tecnología, Universidad de La Laguna (ULL), 38200, La Laguna, Tenerife, Spain.
Phone: +0034 922 316502

[2] Departamento de Técnicas y Proyectos en Ingeniería y Arquitectura, Escuela Politécnica Superior de Ingeniería, Universidad de La Laguna (ULL), 38200, La Laguna, Tenerife, Spain.

[3] Departamento de Economía, Contabilidad y Finanzas. Universidad de La Laguna, Camino la Hornera, 37, Facultad de Economía, Empresa y Turismo, La Laguna, 38200, Spain.

Abstract. The decarbonization of the power sector is undertaking a global transformation with different roadmaps, inclusion of new generation technology and different legal frameworks. In the last years, the costs of renewables have dropped substantially allowing them economically competitive with conventional fuels, in most global markets.
However, the isolated electrical systems are facing a huge challenge to face the energy transition and at the same time, to reach the energy sovereignty, to avoid the external dependence of the energy importation. In this sense, the generation capacity by renewable energies requires the inclusion of enough accumulation capacity to accomplish the generation with the demand curve. Also, the mobility transition will play a remarkable role due to the transition to electrical, hybrid and e-fuels powered vehicles.

Key words. Energy transition, H_2, energy management, energy sovereignty.

1. Introduction

The world is facing, with growing concern, unprecedented, accelerated climate change. The latest report from the Intergovernmental Panel on Climate Change (IPCC) reflects that each of the last four decades have been successively warmer and that global warming is likely to reach 1.5°C between 2030 and 2052 [1–3]. This climate change is directly related to the increase in greenhouse gas (GHG) concentrations since 1750, which are caused by human activities. In this way, the IPCC encourages governments to accelerate their energy transition to reduce dependence on fossil fuels [4].
The EU has taken on the challenge of carrying out its energy transition. The set of EU measures called the "Winter Package" includes in its governance regulation the obligation, for all member states, to develop a national plan that establishes decarbonization objectives. Spain has complied with this obligation by preparing the National Integrated Energy and Climate Plan (PNIEC) in which the objectives for 2030 are to reduce GHG emissions by 23% compared to 1990, reaching 42% of renewables over use end of energy and improve energy efficiency by 39.5%. The PNIEC contains specific measures for electricity generation and land transportation that should lead the reduction of GHG emissions [5].
However, transferring these objectives to the different regions is not an easy task and it depends on the specific characteristics of each territory [6]. In the case of the Canary Islands, this dependency is very high (around 80% in the case of electricity generation). Therefore, decarbonization is an opportunity to achieve greater energy autonomy. Achieving this objective entails a profound change in the economy of the islands and must be adjusted to each island system, as they present differential particularities.
The energy systems of the Canary Islands are particularly isolated due to the great sea depths between islands, so they depend on the importation of the fossil fuels. On the other hand, Canary Islands offer an excellent renewable resource (hours of sunshine and wind), but the massive development of these technologies could cause significant operational problems due to their interruptible and irregular nature, mainly due to the configuration of electrical networks, poorly meshed, and the technical operational restrictions that isolated electrical systems have.
The introduction and development of renewable energies complemented by storage systems are an interesting alternative to conventional models based on fossil fuels, from a socioeconomic and environmental point of view. The regional government has faced this situation with the Declaration of Climate Emergency, approved unanimously by the Parliament of the Canary Islands in 2019. This declaration sets the main objective of achieving the complete decarbonization of the Canary Islands by 2040 [7].
In this sense, several technologies have been evaluated in the declaration, where highlight the accumulation through hydropower, distributed stational batteries, and the use of H_2 as an energy vector.

In the future scenarios, the mobility plays an important role in the energy demand, due to the transition from the internal combustion vehicles to other mobility models without emissions, where the electrical vehicles (EV) are considered as the main alternative for the light duty vehicles. Therefore, the electrification of the economy is strongly dependent on the evolution of the demand for EV. In this sense, optimized recharge profiles will establish future penetration scenarios [8–11]

Recent studies have indicated the proposed scenarios in the Canary Islands strategies are facing different socioeconomic problems to achieve the proper goals [1], mainly due to the economical constrains and the consumer distrust in the use of electric cars, together with the limited development of an effective charging infrastructure.

Considering the requirements of the H_2 production in Canary Island, this article analyze future scenarios to evaluate the reduction of the forecasted electrical demand when e-fuels and H_2 vehicles are introduced as an alternative to EV.

2. Materials and methods

A mathematical model based on EnergyPlan models [12] and economical dispatch in isolated systems have used to evaluate the current Tenerife's energy system and the specific objectives set for energy decarbonization for the island of Tenerife (future Tenerife-La Gomera electrical system) [13].

EnergyPlan is a software program designed for simulating the operation of entire energy systems, typically on an hourly basis. Developed by the Sustainable Energy Planning Research Group at Aalborg University in Denmark [14]it offers a user-friendly interface for modeling various sectors, including electricity, heating, cooling, industry, and transportation. This comprehensive approach allows researchers and planners to assess the impact of different strategies on energy use, efficiency, and integration of renewable energy sources.

The software's strength lies in its ability to handle complex systems with high temporal resolution. By simulating energy flows on an hourly basis, EnergyPlan can account for the fluctuations inherent in renewable energy sources like wind and solar power. This detailed analysis is crucial for designing robust energy systems that can reliably meet demand while minimizing environmental impact [15,16].

stands as a valuable tool for simulating and analyzing complex energy systems. Backed by a user-friendly interface and its ability to handle high temporal resolution, the software empowers researchers and planners to explore various strategies for achieving sustainable and reliable energy futures.

In the models, energy demand has been considered summing all the contributions from the electrical system (grid and self-consumed), and the electrical vehicle demand for land transportation. To carry out the models, we have neglected the energy demand from air and ship transport sectors, both national and international.

Firstly, a 2040 scenario with a total decarbonization of the electrical system has been defined considering the current state and according to the Canary Island Plan for decarbonization (PTECan) [1]. To calculate the aggregated demand, we rely on data on past demand behavior and patterns (specifically from the years 2013 to 2019).

For electricity demand, a study of hourly demand has been carried out to obtain a future projection, considering working and non-working days in the week, differentiating between the months of the year.

Subsequently, we have performed a sectorization of the electricity demand into three main groups depending on the final use sector: services, domestic and industrial. Hence, we have forecasted the future scenarios according to PTECan energy plan.

On the other hand, for land transport we have considered the demand for the vehicle fleet on the islands of Tenerife and La Gomera. To do this, we consider the maintenance of the current (or planned) vehicle fleet, also considering the evolution of EV sales over the total. Subsequently, these new vehicles were added to the electrical consumption, assuming a load profile and average consumption (published in the PTECan strategies).

Using the demand of the electricity and transportation sector, the model aims to supply energy through production with various technologies. Firstly, we have the non-manageable renewable energy (wind, offshore and photovoltaic). Using these three technologies, a modeling of resource patterns (wind and solar radiation) has been proposed over the years of simulation. These patterns have a strong monthly seasonality; thus, future years have been simulated by randomly joining the patterns of previous months. Once these renewable profiles for future years are obtained, we calculate the production with these three technologies.

For self-consumption, the photovoltaic resource pattern profile has been used, and self-production of energy has been integrated into a hybrid system with batteries. Thus, part of the demand will be covered by these facilities and the other is covered by large-scale technologies connected to the network. Network losses are assigned to the latter, which are estimated through trend modeling of the history of annual network losses by month.

The result of electrical demand and network losses is what the model considers should be covered with the different generation technologies. To cover this electrical energy in the first place, we use a conventional technical minimum of the current production technologies installed in the islands.

Technical minimum is defined as the minimum power at which conventional technologies have operated in the historical data period. Above the technical minimum, the hourly production of non-manageable renewable technologies has been added. Finally, this production adjusts to demand, leaving hours with a production deficit (which we complete by adding conventional or with storage) or with overproduction. For this last case, if the scenario contains energy storage or demand management systems, this overproduction will feed this type of technologies. If this overproduction persists, this excess energy will be an energy surplus from non-manageable renewables, which translates into set orders from the network operator, and therefore, we will lose aforesaid energy.

Among the energy demand management systems, we have modelled a series of electrolyzers to produce green hydrogen using the generation surpluses. This hydrogen

will have a double function: to be used in thermal power plants to dispense with other fuels and its use for land transportation.
The final output of the simulation models provides results on the participation of renewable energies, surplus or spilled energy [17], CO_2 emissions, the cost of generating electricity and fuel dependency, under the proposed scenarios. In this line, we will also work with the considerations of the technical minimums of conventional generation equipment, the introduction of storage and the requirements of synthetic inertia [18]. An evaluation of the electrical network and the optimization of power flows to guarantee operating conditions and requirements [19,20] have been performed to accomplish the requirements and constrains of the isolated energy systems regarding the Spanish grid codes applied to isolated territories [21].
Tenerife Island belong to the Canary Islands archipelago, in, Spain, in from of the Morocco coast. Tenerife is an isolated energy system, with an actual peak demand around 600MW. The energy demanded are satisfied mainly by fossil-fueled thermal power plants, with a share of 80% and a renewable penetration of 20% of the total generated energy. Nowadays, in Tenerife there are around 808.100 vehicles and approximately 531.570 are utility cars.

3. Results and discussion

Using the described model and according to the PTECan plan for the energy transition, the total decarbonization is achieved in 2040, using a combination between different generation technologies. The used parameters are show in Table I.

Table I. – Generation technologies in Tenerife in 2040.

Generation technologies	Power (MW)
Conventional generation	0.0
On-Shore Wind	1700.0
Off-Shore Wind	505.3
On-shore photovoltaic	1650.0
Off-shore photovoltaic	27.0
Self-consumption photovoltaic	829.0
Minihydraulics	2.6
Medium/high enthalpy geothermal	20.0
Biomass	17.8
Wave drive	5.0
Solar thermal	0.0
Total installed capacity	4756.7

For the main model, a storage at the user level of 1.219 MWh and at the distributed level of 86.12 MWh is defined. In addition, a ratio of 3.17 obtained from data from a storage container manufacturer will be used.
The values have been obtained directly from the PTECan models and published by the Canary Island Government [1]. One of the most important goals set out in the strategies is the disappearance of thermal generation by the year 2040, which is why it is defined that this type of production will be zero. On the contrary, renewable sources continue to grow, reaching 1,700 MW in the case of on-shore wind, closely followed by on-shore photovoltaics with 1,650 MW, to a lesser extent by self-consumption photovoltaics with 829 MW and finally the off-shore wind power, and offshore photovoltaic technologies, with 505.30 MW and 27 MW.
In this scenario, the demand reaches a value of 5.273 TWh, mainly due to the electrification of the vehicle fleet, which increases every year. Regarding to the electrical vehicles, the required energy fleet is shown in Table II.

Table II. – Energy consumption of the electrical fleet.

Vehicle type	Number of vehicles	TWh/year
Truck	220451	0.6160
Van	150927	0.2711
Bus	5845	0.2733
Utilitarian	1077767	1.2899
Motorcycle	108427	0.0226
Others	24922	0.0382
TOTAL	1588339	2.5111

Finally, it is estimated that land transport will consume 2.51 TWh by 2040. To analyze how the electrical system is working, considering the values of the Table I, we have simulated 2040 year and selected one day to facilitate the understanding of the energy balance. The results are shown in Figure 1.

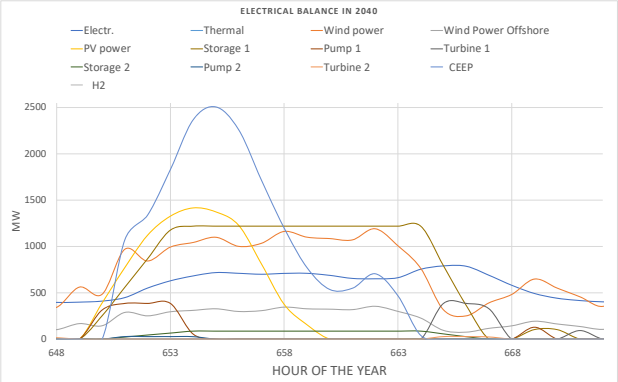

Fig.1. Results obtained from the EnergyPlan simulation of the 2040 year.

The energy demand reaches about 700MW peak, during the evening hours (Electr.). The amount of renewable energy production that cannot be absorbed by the system, (CEEP) and it is stored by batteries and reverse hydropower. Also, the available energy than has not been stored, is used to produce H_2, to be used in the turbines to obtain electricity and accomplish the energy demand.
In this annual balance, the energy surplus obtained from the renewable energy generation and used to H_2 production is shown in Table III.

Table III. - Hydrogen production systems to meet demand in 2040.

Electrolyzer	90	MW
Total wind production	861316	MWh
Total photovoltaic production	508906	MWh

EERR production destined for hydrogen	612837	MWh
Hydrogen produced	1057	kgH_2/h
Hydrogen produced annually	9260	tH_2/año
Maximum production	1360	kgH_2/h
Capacity factor	78	%
Average electrolyzer power	69959	kW
Hydrogen Storage	477,482	GWh

The influence of hydrogen on the system has been considered taking into account the need of the minimum technical value, and therefore, the critical excess of the energy will increase and consequently the accumulation needs or electrolizer power increment to manage the energy excess detected during the year.
The simulation of the year 2040 reveals that higher values of renewable generation and the aggregated demand, greater accumulation is necessary to guarantee the energy requirements of Tenerife electrical system.
Furthermore, by containing 100% renewable generation and the electrified vehicle fleet, CO_2 emissions take on minimum values of 18.27 Mt, solely due to air and maritime transport.

4. Conclusions

In this sense, the analysis of the results reveals the energy demand for land transportation represents almost the 50% of the required energy of the island for 2040, which requires that the installation of renewable energy be increased to be able to supply the total demand required by the year 2040.
The decarbonization of the generation parks on the island of Tenerife requires having to install a greater amount of equipment in order to generate the energy needed, mainly due to the variability of renewable resources, which implies massive storage within the system.
Until now, in literature and energy planning in isolated territories it has been considered that there is a gradual dismantling of conventional generation equipment and therefore, an absence of the existence of a technical minimum of generation, but if we want to make the use of hydrogen in electrical systems, hydrogen turbines must be used. Therefore, it is relevant to consider the size of these teams and take into account their technical minimums.
On the other hand, in a first approximation, if hydrogen is used to generate electricity, the efficiency of the process is around 20%. If instead of considering a complete electrical transition in an isolated electrical system, as seen in this work, a partial transition is considered, where cars that run on hydrogen cells are introduced, where the efficiency is 40%, it would be reduced. considerably the total demand for electrical systems.

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