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Full Road Transport Sector Transition Towards 100% Autonomous Renewable Energy Supply in Isolated Systems: Tenerife Island Test Case

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Abstract: The transition towards sustainable energy systems is a key challenge faced by society. Among the different sectors, road transport becomes one of the most difficult due to the large energy consumption and infrastructure requirements. In this context, although zero-tailpipe-emission vehicle adoption is seen as a promising route, the energy provision through renewable sources is still uncertain, especially with hydrogen. This paper explores a 100% renewable energy supply scenario for both power-generation and road transport sectors in the isolated system of Tenerife. With this aim, the island's energy system has been modelled in the software EnergyPLAN. Taking as reference the current renewable technology roadmap in the island, the impact of a full deployment of zero-tailpipe-emission vehicles on the energy system has been evaluated, providing the power and energy storage capacity requirements. The obtained results indicate the need for 6 GW of renewable power (nearly 20 times the current figures) and 12 GWh of a yet non-existent storage capacity. This deployment must be accompanied with approximately 1 GW of dispatchable sources and 1.3 GW of electrolysis capacity to carry out a complete decarbonisation of the transport sector in the island. Finally, a series of recommendations to policy makers are suggested to support the definition of future roadmaps.

Keywords: autonomous renewable energy supply; isolated energy system; road transport; electrification; decarbonisation

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1. Introduction

Worldwide transport emissions, with nearly 8 Gt CO_2 in 2022, have grown at an annual average rate of 1.7% since 1990 [1]. With an oil dependence of approximately 91%, the transport sector accounts for approximately one-quarter of global anthropogenic CO_2 emissions [2].

In the European Union, road transport represents approximately 70% of the transport sector's CO_2 emissions. Among the different modes, light-duty vehicles (LDVs) are by far the group with largest emissions with 60.6%, followed by heavy-duty vehicles (HDVs) contributing to 38% [3]. To face this situation, the European Union has launched a strong push to adopt more sustainable road transport driven mainly by the European Green Deal and the Sustainable and Smart Mobility strategy [4]. In addition to several aspects that cover the use of low-carbon fuels, the roll out of public charging for light- and heavy-duty vehicles, the EU established that all new cars and vans that come on the market from 2035 must have zero tailpipe emissions. In addition, the EU set the ambitious milestones of at least 30 million of these vehicles operating on European roads by 2030, and nearly all cars, vans, buses, as well as new heavy-duty vehicles being zero-emission vehicles by 2050.

Recently, the Council of the European Union ratified the approved revision of the HDV CO_2 emissions standards [5]. Compared to the 2019 levels, the new standards for almost

all new HDVs with certified CO_2 emissions must provide 45%, 65%, and 90% reductions from 2030, 2035, and 2040, respectively. In addition, all new buses providing urban services must be zero-tailpipe-emission vehicles from 2030.

The aforementioned objectives involve a progressive substitution of the fleet vehicle technology over the coming years. This additional energy must be covered by a greater penetration of renewable energy (RE) [6,7], which eventually puts pressure on the grid and requires a massive deployment of energy storage systems to avoid energy spill. Among the different storage technology options, hydrogen-based storage systems and their use to generate synthetic fuels for sectors where direct electrification is challenging could play a key role in increasing the RE share in the primary energy supply [8]. However, further research and development are still needed to reduce electrolysis cost [9], ensuring its viability. In addition, the hydrogen supply chain must be carefully studied and planned [10], as there is no infrastructure in place to support the technology's deployment.

In this context, small-to-medium isolated energy systems are the most vulnerable. Their geographical conditions restrict their willingness to be self-sufficient and also generate significant economic costs [11]. In addition to this, a small power grid size is a barrier for the mass penetration of renewable sources, as large quantities can generate an imbalance in the network, endangering its stability and generating intermittency problems in almost all networks [12].

1.1. Literature Review

Due to the singularity of the isolated systems, the impact of battery electrical vehicles (BEVs) on isolated grids has been studied in the literature. A common characteristics of an isolated energy system is the noticeable dependence of fossil fuels (especially diesel) for power generation [13], therefore decreasing the benefit of EV adoption to reduce the overall CO_2 emissions. Several authors have tried to quantify reduction figures in representative small-to-medium islands. Applying a Well-to-Wheels approach, a deployment of EVs might bring CO_2 reductions with respect to conventional powertrains between 0 and 20% and 40 and 50% for RE penetration levels ranging from limited up to 20% [14,15]. In addition, these studies reveal that hybrid powertrain architectures currently provide similar CO_2 reduction figures, requiring a much larger RE penetration to enlarge the abatement potential [16–18].

Many studies have been focused on the EV possibilities to promote the integration of renewable energy and to reinforce the grid stability [19–21]. To face the variability and uncertainty issues of the resource, there are mainly two approaches: (i) by means of controlling methods, where a limitation of the quantity of the renewable energy in the grid is achieved, or (ii) by means of energy storage systems [22], where larger energy penetration could be reached [23]. Therefore, it has been demonstrated that the BEVs can perform a two-way delivery of energy, improving the peak-shaving effect and reducing the need for conventional power plant generation [24].

On the contrary, a large deployment of BEVs entails a remarkable additional load to electrical systems, hindering the optimal management of the grid constraints and making necessary a precise planning of the grid to avoid undesirable electrical problems [25–27]. In this context, previous studies report that uncertainties in EV charging and RE resources could require up to a 30% increase in the installed power capacity from the estimated one to cover certain demands to avoid an energy shortage risk [28].

One relevant aspect is the BEV capability to act as an active element through Vehicle to the Grid (V2G), allowing the interchange of power between the electrical grid and the vehicle. The application of V2G technology can contribute to peak shaving, self-consumption, frequency control, reactive power compensation, and, when introduced in a larger scale, this technology rises the share of renewable energy in the energy mix [29]. In this sense, previous results have revealed a reduction of both grid harmonics and frequency deviation, favouring the integration of variable energy sources into power grids [30]. In addition, V2G penetration can be adequately used to avoid grid overloading and load matching [31–33],

reducing the renewable energy surplus and therefore turning into a reduction of the renewable capacity needed. Other studies have highlighted the benefit of V2G penetration to reduce the undesired effects of the reactive power generated by the power electronics in various types of small- and medium-size distribution networks through a proper combination of charging stations location and management algorithms [34].

Several research works have studied decarbonisation scenarios in isolated energy systems, where the EV penetration and its interaction with the grid are not considered in detail and the HD transport demand is dismissed [35–37].

Despite the multiple contributions to the state of the art, the literature survey related to transport decarbonisation in isolated systems reflects that the majority of works have addressed specific topics. However, analysis that covers how the isolated energy system must evolve to accommodate the energy transition of the whole vehicle fleet (light- and heavy-duty) considering energy sovereignty have been dismissed. The present research work is devoted to filling this gap by means of evaluating a full transition scenario of road transport from a renewable energy autonomy standpoint. First, a complete transition of the power-generation sector is studied to later address the impact of the transport sector demand on the energy system response. The provided figures of energy demands, new power and storage capacities, and the efficiency indicators represent a solid contribution to general knowledge. In addition, the obtained results point out the main bottlenecks of this route, which allows policy makers and industry stakeholders to develop future roadmaps.

1.2. Tenerife Energy System

Tenerife, Canary Islands, with an area of 2034.38 km² and a population of 944,107 inhabitants is the largest and most populated island in Spain. Located in the Atlantic Ocean and close to the African coast (see Figure 1), Tenerife is one of the European Union's outermost regions.



Figure 1. Geographical location of Tenerife, Canary Islands.

A basic representation of this isolated energy system is depicted in Figure 2, developed with the most recent published data (2022) [38]. Oil (mainly heavy fuel oil, diesel, and petrol) is the dominant primary energy source, exceeding the 22 TWh of energy import. The two main demand sectors are power-generation (29.06%) and transportation (70.94%). Oil consumption in the industrial/service sectors and LPG, although existent, has been omitted as its values are relative low. Renewable sources (mainly WE and PV) only represent 2.8% of the total primary energy consumption, making clear the great dependence on fossil fuels across all sectors.

In 2022, the electricity demand was 3.4 TWh/year, with a peak power of 557 MW. A total share of 84% of this demand was covered with conventional sources, a common factor in other isolated power systems [11,38,39]. The current structure of the power-generation sector is summarised in Table 1, which includes the technology, power capacity, generation share, and fuel type. Combined Cycles and steam turbines supply most of the required power and provide the base load, with a total share of 74%. The rest of the technologies are two-stroke marine-derivative compression ignition engines and gas turbines, the latter being mainly used to support peaks and provide a spinning reserve. With no infrastructure in place to deploy natural gas, gas turbines make use of diesel fuel, whereas heavy fuel oil is the current fuel to feed the two-stroke engines and steam turbines.

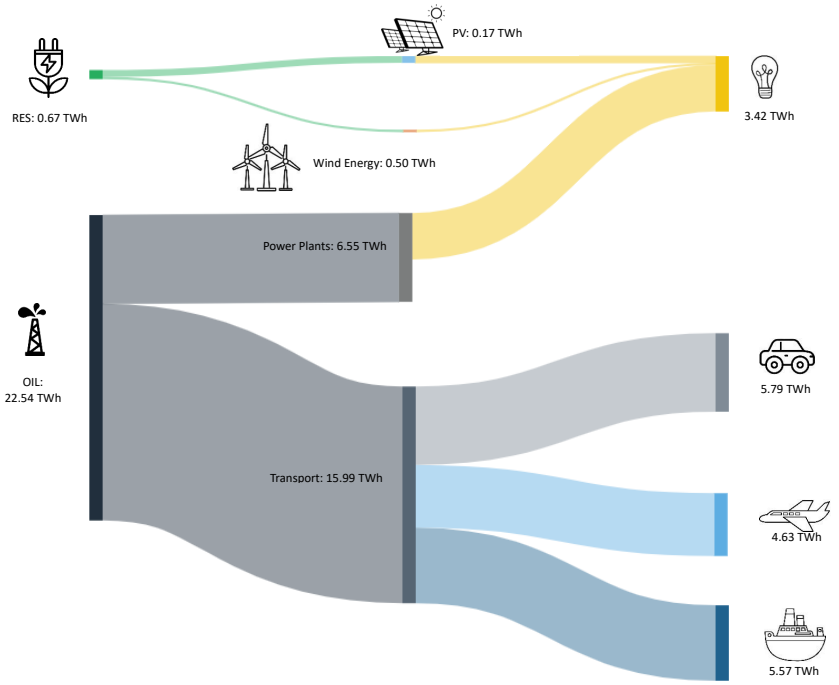


Figure 2. Sankey diagram of current energy system of Tenerife island. Data extracted from [38].

Table 1. Description of the current power-generation system of Tenerife. Data extracted from [38].

Technology	Gross Installed [MW]	Generation [GWh]	Share [%]	Fuel	Average Thermoelectric Efficiency [%]
Combined Cycle	457	1943	54.2	Diesel	47
Steam turbine	160	706	19.7	HFO	33
Gas turbine	248	99	2.8	Diesel	24
Diesel engine	48	149	4.1	HFO	43
Wind energy (WE)	222.6	508	14.2	-	-
Solar photovoltaic (PV)	107.6	168	4.7	-	-
Small hydropower	1.2	3	0.1	-	-
Biogas plant	1.6	9	0.3	Biogas	-

As a result of the technical difficulties to reach large RE penetration percentages [40], the current contribution of RE technologies to the electrical energy produced on the island is 19.2% (17% across this archipelago) [38]. This percentage is considerably far from interconnected systems such as mainland Spain, where the current figure is 48.4% [41].

The road transport sector, with a fleet mainly powered by internal combustion engines (ICEs), has an oil demand of 5.79 TWh (25.68% of the total demand). The breakdown consumption, grouped by vehicle application and fuels, is shown in Table 2. The oil demand of LDVs, including passenger cars and vans, represents 65% of the total road transport demand. The fleet (approximately 800k vehicles) [42] is dominated by petrol

engines, as the consumption per fuel type evinces. The rest of the conventional vehicles uses LPG as fuel (energy demand of 7.73 GWh), representing only 0.21% of the total fleet [38]. Plug-in vehicles account for 0.54% of the LDV fleet [42]. Their share in the new registered vehicles has moved from 1.37% in 2019 to 12.28% in 2023 [42], confirming a progressive technology shift due to government incentives.

Table 2. Oil-based annual energy consumption of road transportation.

	LDV Energy Consumption [TWh]	HDV Energy Consumption [TWh]
Petrol	2.52	-
Diesel	1.21	2.03
Total	3.73	2.03

HDVs represent 36% of the road transport energy demand and almost 10% of the total oil imported to the island. In this case, diesel is practically the only source of power, as the petrol HDV share is negligible and battery electric buses for urban services are still being commissioned.

1.3. Decarbonisation Strategy

The regional government has recently published the PTECan-2030 (Plan de Transicion Energetica de Canarias), that establishes a roadmap to decarbonise the Canarian energy system. This main objective is divided into several specific objectives: energy autonomy, decarbonisation of the economy, electrification of heat/cooling and transport demands, as well as progressing in circular economy approaches. Although the PTECan plan envisages a full decarbonisation of the economy in 2040, only domestic-specific goals are set for 2030, described as follows:

- A 62% share of RE in the generated electricity.
- A 29% of RE share in the total final energy consumption.
- A 27% of energy efficiency improvement.

The PTECan plan does rely on a series of specific studies covering aspects such as net metering potential [43], energy storage [44], transport electrification [45], future dispatchable power generation [46], or the deployment of H_2 as fuel [47]. An in-depth analysis of future energy demands and transport evolution was performed as a basis to propose the suitable energy system structure subjected to a series of identified constraints.

With respect to the power-generation sector, the plan for Tenerife proposes a massive deployment of renewable sources in the 2025–2040 timeline. From the current value of 333 MW, the strategy suggests that RE capacity will be increased by approximately 14 times, as Table 3 depicts. In this context, PV, both self-consumption and utility scale, would experience a significant growth, with 2302 MW. The plan also relies on increasing the on-shore WE capacity by 7.5 times, by means of installing new units and re-powering the old ones. Off-shore WE will also play a key role in the future energy mix, as the plan expects 505 MW. To a lesser extent, geothermal and wave energy will also be introduced in the energy system, with 20 MW and 5 MW, respectively. The plan also points out the need for 210 MW of firm generation provided by gas turbines, using internally generated H_2 from renewable sources.

Although the PTECan-2030 lacks clarification regarding the energy storage systems (ESSs) for the island of Tenerife, the specific strategy supporting the plan does rely on a significant deployment of user-based EES (batteries) accompanying the expected massive penetration of self-consumption PV. Up to 2.5 GWh of available EES is expected, allowing higher rates of PV share in the power-generation mix. Distributed EES, located across the different electricity substations, could also reach the significant figure of 1.1 GWh. The space constraints and the orography of the island limit the deployment of large-scale energy storage systems, such as pumped storage hydropower, compressed-air energy storage or Liquid Air Energy Storage. Multiple assessments regarding plant locations

have been conducted [44]. Current projections suggest 300 MW/4800 MWh of maximum capacity for this kind of system. Any additional energy storage requirements will be covered by batteries.

Table 3. Current structure and PTECan proposal for renewable energy and energy storage capacities in Tenerife.

	Current System [38]	PTECan [48]
Wind On-shore [MW]	222.6	1700
Wind Off-shore [MW]	0.0	505.3
PV On-shore [MW]	107.6	1650
PV Off-shore [MW]	0.0	27
PV Self-Consumption [MW]	38	829
Wave Drive [MW]	0.0	5.0
Small Hydropower[MW]	1.2	2.6
Biogas [MW]	1.6	17.8
Geothermal [MW]	0.0	20.0
H_2 turbines [MW]	-	210
EES–User [GW/GWh]	-	2.6/2.5
EES–Distributed [GW/GWh]	-	1.1/1.1
EES–Large Scale [MW/GWh]	-	313/5.2

From PTECan's perspective, BEVs will be the dominant technology across the light-duty transport sector. From the current low figures of a 12% share in new registrations, BEVs will progressively take the place of ICEs until the total abandonment of fossil fuels. In the context of the heavy-duty transport sector, Fuel Cell Electric Vehicles (FCEVs) will be the major technology to replace the diesel fleet.

Although the work behind the aforementioned strategies has been extensive and covers the entire period until decarbonisation, the final PTECan plan, which is a combination of the most relevant outcomes, lacks clarity defining the future energy demands and technology deployment beyond 2030. The aim of this paper is to provide an insight into this future plan, by complementing the results and extending the analysis to the full decarbonisation of both sectors from an autonomous energy supply perspective. The paper is organised as follows. Section 2 is devoted to explaining the methodology applied within this research work, covering the model configuration in EnergyPLAN and its validation. In Section 3, a description of the problem statement and the required energy system structure to meet the decarbonisation with autonomous energy supply goals are covered in detail. In the discussion, conclusions, and policy implications, the authors provide a set of recommendations based on the data gathered that might support future roadmap revisions.

2. Materials and Methods

2.1. EnergyPLAN Simulation Tool

The nature of this work requires the use of a bottom-up approach, as both energy sectors and technologies must be analysed in detail. EnergyPLAN, HOMER or H2RES are examples of the bottom-up model options that can be found in the literature. Among them, the free and user-friendly software EnergyPLAN v16.2 (Aalborg University, Aalborg, Denmark) has been selected as it is one of the most used tools to perform energy planning and support energy decision makers [49].

The EnergyPLAN tool applies a purely deterministic simulation approach with a description of all sectors: electricity, heating, cooling, industry, and transportation. Developed by Aalborg University, EnergyPLAN has been specifically designed to assist in the design of planning strategies under the theory of Choice Awareness [50]. Instead of applying numerical solvers to resolve optimisations, the software uses an heuristic approach, performing hourly energy balances and taking a set of predefined dispatching priorities [51]. This fact, together with the sectorial aggregation principle, significantly reduces the computational effort, being able to run a one-year period in just few seconds.

Figure 3 includes an overview of the software structure. As inputs, the user can define the main aspects of the analysed energy system: the different energy demands, the renewable energy sources, the capacities of the energy stations, the costs, and the regulation strategies. Among the outputs, EnergyPLAN provides the energy balance and the resulting annual production, fuel consumption, electricity import/export, CO_2 emissions, etc. [51]. Additional description of the software can be found in [52].

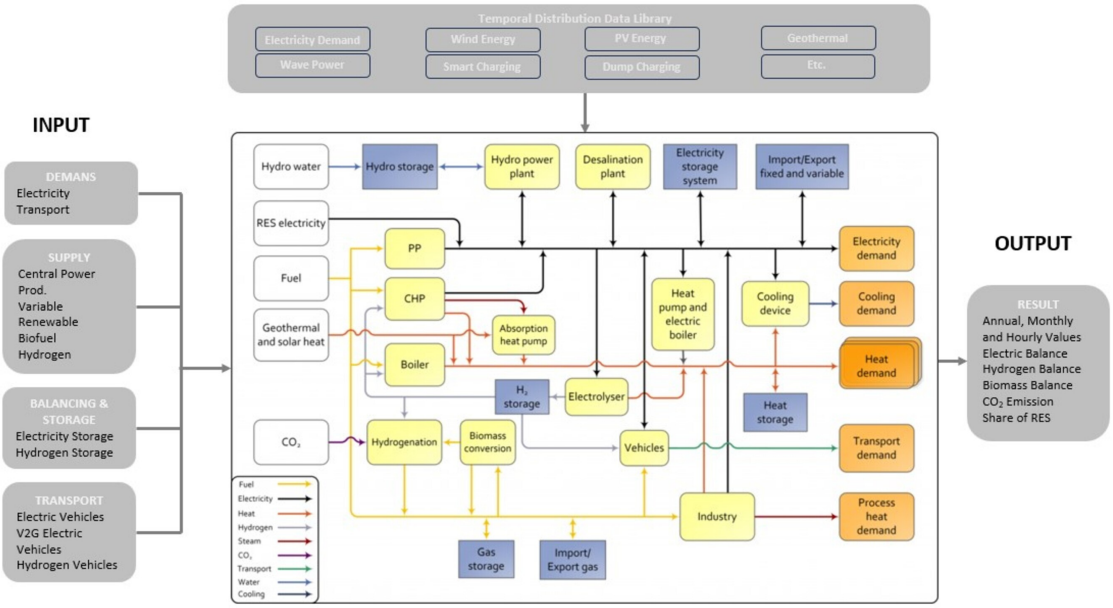


Figure 3. EnergyPLAN model structure. Definition of inputs/outputs. Adopted from [51].

EnergyPLAN has been widely applied in energy planning exercises with a special focus on sustainable energy solutions [51] at national [53], regional [54], and local levels [55]. The literature also reports that EnergyPLAN is one of the most common tools applied to evaluate isolated systems [49]. Although these systems might bring additional constraints such as reliability and robustness of the power grid, EnergyPLAN can successfully address them using alternative methods based on specific indicators. Several application examples taking, as a test case, isolated island systems, like the present research work, can be found in the literature [55,56].

2.2. Baseline Model Configuration and Validation

The energy system of Tenerife (described in Section 1.2) was modelled in EnergyPLAN. The baseline model was configured according to 2022 data, the most recent and representative year with a complete available dataset [38]. The input data applied to the model are described as follows:

- The aggregate demands for electricity (grid) and transport oil demand.
- The hourly distribution of electricity demand and the renewable energy production (WE and PV), extracted from data registered by the system operator [57].
- Grid technical restrictions, incorporated to the model as a minimum baseload. A value of 140 MW was applied based on previous history [57].
- Power-generation installed capacities and the average thermoelectric efficiency of the conventional powerplant [38].
- Heat/Cooling power demands were discarded as they are negligible compared to the rest of demands.

Once the model of the energy system was configured, the next step comprised the validation phase. With this in mind, the years 2019–2022 were simulated, imposing the input parameters described above. The same normalised profiles for electrical demand and

WE/PV generation (2022 data) were used across every test case, therefore only changing the aggregate demands and power capacities. The model was considered valid if the RE energy production and conventional generation/oil consumption were close to the data published.

Table 4 includes the main results of the validation phase. The simulation outputs in terms of annual electricity demand (just for reference, as it was imposed), RE generation, and the conventional park performance are compared against published data. The same values for simulated WE generation are found in the years 2019–2021, as no new capacity was installed in those years and the same normalised generation profiles were used. The same reason applies to simulated PV generation across the four years (no changes in capacity).

Table 4. Energy system model validation.

	2019			2020			2021			2022		
	Model	**Data [58]**	**Error [%]**	**Model**	**Data [59]**	**Error [%]**	**Model**	**Data [60]**	**Error [%]**	**Model**	**Data [38]**	**Error [%]**
Demand [TWh]	3.55	3.54	0.06	3.17	3.16	0.09	3.25	3.25	0.15	3.42	3.42	−0.06
WE generation [TWh]	0.48	0.49	3.08	0.48	0.48	0.77	0.48	0.52	−8.40	0.50	0.50	0.00
PV generation [TWh]	0.19	0.19	0.52	0.19	0.17	7.34	0.19	0.18	3.83	0.19	0.18	2.15
Oil demand (generation) [TWh]	7.37	7.57	2.64	6.42	6.37	0.71	6.61	6.57	0.66	7.18	7.16	0.28
Peak grid demand [MW]	571	576	0.87	510	556	−8.27	522	529	−1.32	551	557	−1.08

The low error values in predicting the annual renewable energy production, below 8.4%, evince that the annual energy source variability is not high, and, therefore, the same normalised profiles can be applied without introducing important errors to assess future scenarios. The acceptable estimation of RE generation ensure an accurate representation of the electrical energy generated and oil consumption of conventional generators, even in the event of a drop in demand for both 2020 and 2021 associated with the lockdown during the COVID-19 pandemic. The estimation errors are below 5% in terms of oil consumption with the sources related to the actual gen-sets warm-up/cool-down phases during the operation, as the model does not take this into account. Overall, the acceptable accuracy figures provided by the model confirm that it can be used with confidence to assess future scenarios of the island´s energy system.

3. Results

3.1. Problem Statement: Decarbonisation of Power-Generation and Road Transport Sectors Through Autonomous Energy Supply

The validated EnergyPLAN model of Tenerife's energy system will be used to illustrate the problem of reaching the status of a fully autonomous and decarbonised energy system in terms of both power-generation and road transport sectors. As a starting point, the regional government targets for RE power capacity and EES previously shown in Table 3 would be considered. The main hypotheses applied when simulating this scenario in EnergyPLAN are described as follows:

- The annual electricity demand is increased from the current 3.6 TWh to 5.1 TWh. The latter figure, extracted from the data supporting PTECan [46], was estimated using multiple regression techniques taking the trends for future population and GDP projections as independent variables.
- The non-dispatchable renewable power capacity per technology is described in Table 3. The validated normalised generation profiles are applied in EnergyPLAN to obtain the power generation of on-shore wind energy and PV. With respect to the off-shore WE, a correction factor to cover the additional 20% of energy availability obtained in several resource measurements in the island [61] is applied.
- The dispatchable power injection would be provided by a high-enthalpy geothermal system (see capacities in Table 3) and gas turbines fuelled with H_2. Neither baseload nor grid stability restrictions were considered in this work. The large amount of energy storage capacity, generation unit hybridisation to provide primary and secondary

control reserves [62,63], or the development and deployment of power electronics [64] support this hypothesis.

- Energy storage capacity was considered at user- (self-consumption), distributed- (electricity distribution system), and large-scale levels. The power and storage capacities are also included in Table 3. The energy storage associated with the self-consumption PV is considered centralised; therefore, the charging and discharging process is modelled based on EnergyPLAN dispatch priorities.
- PTECan assumptions indicate that BEVs will practically be the sole technology across the LDV fleet. In this work, the same criteria was assumed. In order to account for a conservative hypothesis, the LDV energy demand was kept constant. Therefore, the demand of fossil fuels (ICEs) shown previously in Table 2 was shifted to electricity, applying the following expression:

$$Elec_{LDV} = (E_P \eta_{ICE_P} + E_D \eta_{ICE_D}) \frac{1}{\eta_{Char} \eta_{EV} \eta_{trans}} \quad (1)$$

where $Elec_{LDV}$ is the electric demand of the LDV fleet, E_P and E_D are the petrol and diesel energy demands and η_{ICE_P} and η_{ICE_D} are average petrol and diesel ICE efficiencies. Finally η_{EV}, $\eta_{Charging}$ and η_{trans} correspond to the average electric motor efficiency, the charging efficiency, and the grid transportation efficiency, respectively. As a result, the total annual electricity demand to propel the LDV fleet is estimated to be 1.71 TWhe (half of the current overall grid demand in the island), similar to the 1.5 TWhe figure projected by the government in [45]. The dump charging profile (applied in previous works [17]) was extracted from the mobility strategy supporting PTECan [45].

- The PTECan hypothesis relies on the H_2 use as a primary fuel for heavy-duty (HD) transportation through fuel cells. Unlike LDVs, the technology selection for HD transportation is challenging due to the longer distance, power demands, and the wide range of business cases. Therefore, current OEMs' roadmaps are considering BEVs, FCEVs, or ICEs fuelled with renewable fuels such as H_2, biofuels, or e-fuels [65]. In this work, a combination of BEV and FCEV technologies to propel the HDV fleet was considered. Different shares were evaluated with the aim of providing trends of the energy system response to cover the resulted demand in terms of electricity and H_2 (produced internally with electrolysers). Similar to the LDV fleet, the fossil fuel demand was shifted to electricity and H_2, applying the following expressions:

$$Elec_{HDV} = (E_D \eta_{ICE_D}) \chi_{EV} \frac{1}{\eta_{Char} \eta_{EV} \eta_{trans}} \quad (2)$$

$$H_{2HDV} = (E_D \eta_{ICE_D}) \chi_{H_2} \frac{1}{\eta_{FCEV}} \quad (3)$$

where $Elec_{HDV}$ and H_{2HDV} are the electric and H_2 demand of the island´s heavy-duty fleet, E_D is the current diesel energy demand, and $\eta_{ICE_{HD}}$ is the average HD diesel ICE efficiency. η_{EV}, $\eta_{Charging}$, η_{trans}, and η_{FCEV} correspond to the average electric motor efficiency, the charging efficiency, the grid transportation efficiency, and fuel cell efficiency, respectively. Finally, χ_{EV} and χ_{H_2} correspond to the demand share of electricity and H_2, respectively.
Due to the nature of the HD service, the majority of the fleet will be charged overnight. Therefore, only a dump charging strategy was used.

- The required H_2 for both power-generation and transport would be generated by electrolysers. Rather than imposing a predefined operation by the user, EnergyPLAN switches on the electrolysers based on the H_2 demand and the availability of renewable energy. The electrolyser capacity required to cover the H_2 demand will be a simulation output rather than imposed by the user.

The previously mentioned hypotheses required several efficiency parameters to perform the different energy conversions that are fed later to EnergyPLAN. Table 5 includes the efficiencies of the H_2 route (Power-to-H_2-to-Power) and the energy storage charging/discharging processes. The information is completed with the efficiency figures applied to shift from the internal combustion engine-based propulsion demand to both electricity (BEVs) and H_2 (FCEVs).

Table 5. Overall efficiency values applied to obtain the LDV electricity demand.

	Efficiency Values
Average H_2 turbine thermoelectric efficiency	0.40
Electrolysis efficiency	0.75
ESS charging/discharging efficiency	0.90
η_{ICE_P}	0.28
η_{ICE_D}	0.32
η_{EV}	0.86
$\eta_{Charging}$	0.90
η_{trans}	0.93
$\eta_{ICE_{HD}}$	0.39
η_{FCEV}	0.54

3.1.1. Power-Generation Sector

Figure 4 exemplifies the operation of the decarbonised power-generation sector through the condition of full energy autonomy. The road transport demand is been included in order to show its impact in a latter stage. Power injection per technology and the operation of the energy storage system (both electricity and H_2) are shown for two representative weeks. Left-side plots show a week with large WE resources whereas the right-side plot corresponds to limited WE resources.

The remarkable PV generation, together with high wind resources, entail a large amount of RE production, as Figure 4a shows. This excess of RE is mostly employed to feed the electrolysers that generate the gas turbine fuel, as Figure 4c depicts. The remaining renewable power that can neither be injected nor stored (see Figure 4e) is computed as surplus RE energy. The 3rd and 4th days show curtailment levels that reach up to 1500 MW.

Despite the large EES capacity considered in this scenario, a short intermittency of WE generation changes the system's operation considerably. In a first instance, the EES injects power until total depletion (see Figure 4c,e). Then, the H_2 storage level is significantly reduced, since turbines must operate to partially cover the grid demand and there are limited opportunities to switch on the electrolysers. This behaviour becomes critical for larger periods with limited or no WE resources, as right-side plots evince. The island energy system responds with backup power fuelled with H_2, depleting the gas reserves until relevant wind resources are available again. In addition, the PV power excess is mainly used to feed the electrolysers, limiting the available energy to be stored.

A summary of the simulation outcome for an entire year is included in the first column of Table 6. The WE intermittency and the limited PV capacity factor implies a large operation of H_2 turbines, with 1665 h of annual working time and almost 1 TWhe of electricity generation. The simulation results suggest that 650 MW of capacity would be required, similar in size to the current conventional park. The H_2 provision (2.1 TWh) would be supplied with 1.1 GW of electrolysis, demanding 2.8 TWhe of electricity and 0.56 hm^3 of water. The estimated capacity factor exhibits the poor value of 2475 heq, which might put the economic viability into question.

Despite the large storage capacity and the use of H_2 as an energy vector, the estimated amount of RE curtailed is 2.6 TWhe (27.3%). This behaviour, which causes inefficiencies and profitability losses, might discourage the implementation of RE and the entry of private investment capital.

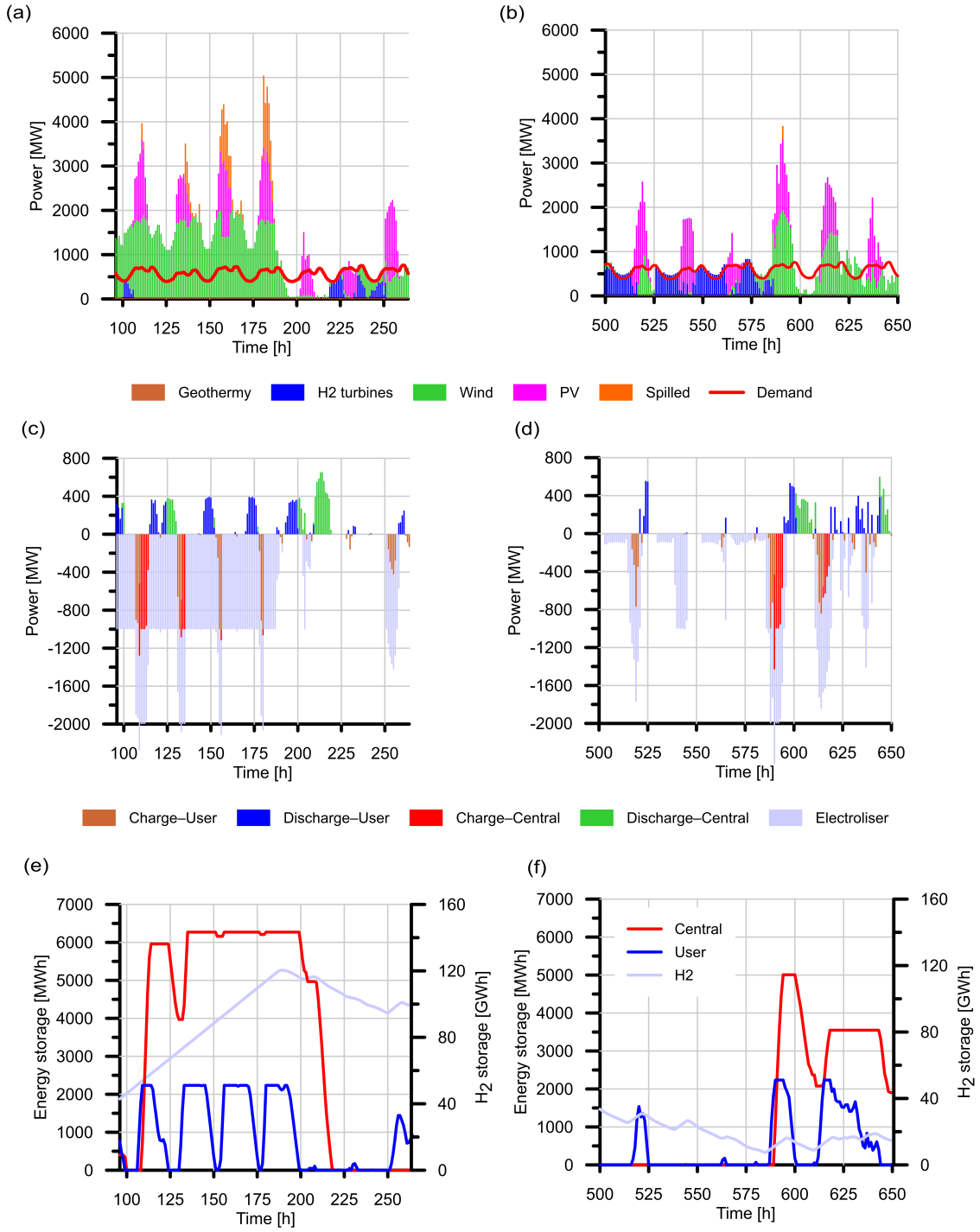


Figure 4. Operation of the decarbonised grid system response with no transport demand considered: representative week with large (**a**,**c**,**e**) and limited (**b**,**d**,**f**) WE resources.

3.1.2. Light-Duty Vehicle Transport Sector

The electrification of the entire LDV fleet through BEVs would result in remarkable changes of the total grid demand (power and profile), as Figure 5a depicts. The expected charging profile in the island, in which overnight charging events prevail over daily and/or opportunistic ones, does modify the grid valley period, increasing the demand from approximately 400 to 600 MW. The average contribution of dispatchable sources (mainly gas turbines fuelled with H_2) during the overnight period is 12%, which means that a considerable amount of the LDV transportation demand would be covered through the Power-to-H_2-to-Power path. Although this route would enable zero CO_2 tailpipe

emissions, the low overall round trip efficiency (28% in this work) requires overcapacity and infrastructure over-design. Peak demand also changes considerably. From an initial estimation of 745 MW with no BEVs considered, the grid demand reaches 827 MW, 44% higher than current figures.

Table 6. Main annual simulation results: autonomous renewable energy supply with and without LDV fleet demand.

	W/O LDV	LDV	LDV–Smart Charging
Demand [TWhe]	5.13	6.85	6.85
H_2 Turbines [TWhe]	0.91	1.11	0.99
Total RE [TWhe]	9.51	13.21	13.21
Wind Energy [TWhe]	3.73	4.15	4.15
Wind Energy Off-shore [TWhe]	1.71	3.62	3.62
Photovoltaic Energy [TWhe]	4.05	5,41	5.41
Geothermal [TWhe]	0.17	0.17	0.17
Wave Drive [TWhe]	0.02	0.03	0.03
Biomass [TWhe]	0.17	0.17	0.17
Curtailment [TWhe]	2.60	4.12	4.36
Curtailment [%]	27.34	31.19	33.01
EES Discharge [TWh]	0.66	0.94	0.69
EES Charge [TWh]	0.73	1.04	0.76
Storage Capacity at Maximum Level [% of time]	36.21	46.70	49.77
H_2 produced [TWh]	2.10	2.60	2.30
Electrolysis Capacity [MW]	1131	1206	1225
Electrolysis Electricity Demand [TWhe]	2.80	3.47	3.07
Electrolysis Operation [heq]	2475	2877	2505
Electrolysis Water Consumption [hm^3]	0.56	0.70	0.62
H_2 Turbine Capacity [MW]	653	877	779

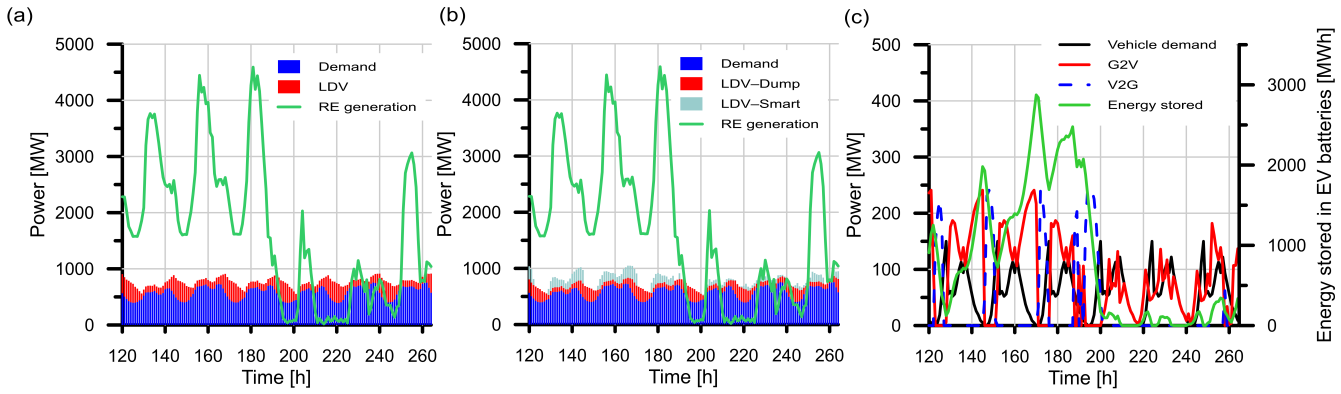


Figure 5. Impact of LDV demand on the grid system: (**a**) only dump charging considered, (**b**) smart charging for 30% of the fleet, and (**c**) example of bidirectional smart charging operation.

Smart charging (G2V/V2G technology) allows moving part of the transport demand to periods with large RE generation, located mainly around midday. In order to assess the impact of this technology on the system response, a sub-scenario was considered where a 30% of the light-duty transport demand was computed as smart charging. EnergyPLAN scheduled vehicle smart charging in periods with excess of RE generation and available battery energy capacity in vehicle batteries. Based on the overall storage capacity and the daily vehicle usage pattern, both imposed by the user, EnergyPLAN computed the hourly overall storage level of the smart fleet. The overall storage capacity value was estimated from the number of vehicles comprising the smart fleet, assuming an average battery capacity of 70 kWh [66] and 80% of the energy available for V2G/G2V functionality. The most recent vehicle usage pattern developed by the local government was imposed [67] to compute the hourly energy consumption and vehicle availability for charging. The charging power was

limited by grid/vehicle connection capacity. A value of 351 MW was employed, assuming that 2 kW of charging infrastructure was available per vehicle (the current ratio in Europe is 1 kW/vehicle) [66].

EnergyPLAN allows power injection from vehicles to replace conventional generation if enough energy is available in batteries. The amount of power is, again, capped by the grid/vehicle connection capacity. Table 7 summarises the input parameters employed to simulate the smart charging functionality in EnergyPLAN.

Table 7. Input parameters employed to simulate the smart charging functionality.

	Values
Estimated smart fleet [-]	175.9 k
Average BEV consumption [kWh/km]	0.2
G2V/V2G connection capacity [MW]	352
Unit battery capacity [kWh]	70 [66]
Overall battery capacity [MWh]	985

Figure 5b,c exemplify the operation of the G2V/V2G functionality and the resulting load profile derived from its potential deployment. In the events of large RE generation (first three days), the grid enables significant charging (G2V) loads, increasing the direct contribution of RE to cover the vehicle demand, reducing the energy spilled and the grid stress at peak hours. The bidirectional power flow can also be observed in those days, with electrical vehicles providing power to the grid while they are parked (V2G) at night-time. The opposite behaviour can be observed in the next three days, with limited RE generation and, therefore, G2V capacity practically restricted to cover the daily vehicle demand.

As the reader can expect, the power-generation structure that provided the annual results previously shown in Table 6 is insufficient to cope with the additional LDV fleet demand. Further contribution of dispatchable sources (H_2 turbines) will be required, which means more H_2 production requirements and, therefore, more electricity to feed the electrolysers. This behaviour turns into a snowball effect, preventing both sectors to meet the goals of decarbonisation with an autonomous energy supply. In order to provide an estimation of the additional resources required to cope with the demand, the RE power and energy storage capacities were increased based on the following criteria:

1. For the sake of consistency with local government planning, the PV/WE ratio was kept constant.
2. Due to space constraints, the on-shore WE capacity was capped at 1700 MW, as previous reports suggest [46].
3. User-based EES was increased according to PV self-consumption growth.
4. Large-scale EES limits were set to 5.2 GWh, based on the estimations carried out by the local government [44].
5. A maximum curtailment level of 30% was considered to set the distributed EES capacity growth.

Table 8 includes the RE structure evolution required to extend the decarbonisation and autonomous supply targets to the LDV sector. An additional 1400 MW of RE capacity will be required (33% increase) to support a fully electric LDV fleet. To put these figure into context, the required additional capacity exceeds 3.9 times the current RE installed in the island. The deployment of additional capacity of non-dispatchable energy sources brings along new requirements for EES capacity, as Table 8 illustrate. Simulation results point out that 1GWh of EES, located at user and distributed levels, must be installed to avoid excessive curtailment levels.

The second column in Table 6 shows the annual results of this new scenario, considering the pre-defined dump charging. The problem of covering the additional LDV fleet demand (1.7 TWhe) with non-dispatchable sources characterised by high intermittency and low-capacity factors can be clearly seen in the tabulated data. To avoid a significant contribution of H_2 turbines that creates the aforementioned snowball effect, 1400 MW is

required, generating 3.70 TWhe but increasing the curtailment level by 1.5 times despite the larger EES capacity. In addition to this, the H_2 turbine backup capacity must be expanded to 1200 MW and its contribution to support the grid demand increased by 200 GWh, which can be supported with a similar electrolyser capacity.

The annual results of testing the same power-generation structure assuming that 30% of the LDV fleet makes use of intelligently managed EV charging are included in the third column of Table 6. Shifting part of the charging loads to periods with larger RE availability reduces the contribution of H_2 turbines by 10%, as it requires a similar power capacity than the reference case without considering transport demand. The lesser electrolyser demand, which operates in periods with RE availability, explains the slightly higher curtailment values. Although the smart charging functionality seems to exhibit a benefit for the energy system, a much higher percentage of the fleet must be incorporated to reduce the RE and ESSs' capacity required for deployment. In addition, the infrastructure requirements are significant and a robust regulatory framework of this bidirectional functionality must be developed and put into practice.

Table 8. Current structure and RE and EES capacities required to reach autonomous supply in power-generation sector and light-duty vehicle transport.

	Current	Power Generation	LDV
Wind On-shore [MW]	222.60	1530	1700
Wind Off-shore [MW]	-	455	961
PV On-shore [MW]	107.60	1485	1980
PV Off-shore [MW]	-	24	32
PV Self-Consumption [MW]	38	746	995
EES–User [GW/GWh]	-	2.4/2.2	3.2/3.0
EES–Distributed [GW/GWh]	-	1.1/1.1	1.3/1.3
EES–Large-Scale [MW/GWh]	-	313/5.2	313/5.2

3.1.3. Heavy-Duty Transport

Although the use of H_2 as fuel for HD transport overcomes the main drawbacks of BEVs related to limited range and charging infrastructure requirements, the impact of its internal production on the energy system response must be evaluated. A parametric study varying the H_2 share as HD transport fuel was performed to illustrate how the energy system structure must evolve to supply the demand. The same five criteria described in Section 3.1.2 have been followed to carry out the simulations.

Figure 6 shows the additional RE and EES capacity requirements to reach full decarbonisation of the HDV fleet with an internal energy supply as a function of the H_2 penetration as fuel. Readily apparent from Figure 6 is the lesser RE and EES capacity requirements with the H_2 share. The different origin of the additional energy required to charge (BEVs) or fill the tanks (FCEVs) explain this behaviour. With respect to BEVs, large electricity demands located during overnight hours significantly stress the grid system. With no direct support of PV, the additional grid demand must be covered by EES (limiting the energy available to support RE intermittency) and H_2 turbines that must operate for longer periods. This behaviour increases the proportion of the low efficient Power-to-H_2-to-Power path. As a result, the RE capacity must be increased to reach 100% autonomy.

The opposite behaviour is observed by introducing higher shares of H_2 fuel. Although the system must generate the H_2 to feed the HDV fleet, the electrolysers' dispatch approach prioritises an excess of RE, turning into a better use of the available energy. Therefore, for energy systems similar to the one examined in this study, the use of H_2 requires less power-generation infrastructure and improves the overall system efficiency, quite the opposite of only taking the vehicle efficiency into account to carry out an analysis.

Regardless of the type of technology employed to propel the HDV fleet, the predicted additional power and storage capacity to be deployed are significant, with 600–900 MW and 2470–2750 MWh of RE and ESS capacities, respectively.

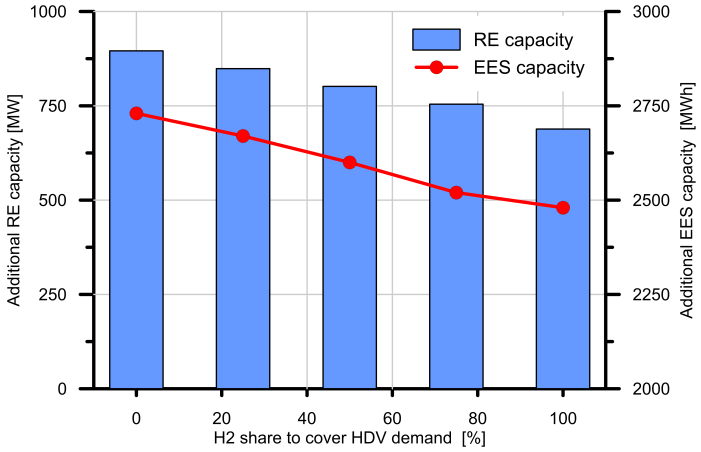


Figure 6. Additional RE and ES storage capacity requirements to reach 100% RE energy supply for the HDV fleet.

4. Discussion

Transitioning to zero-tailpipe-emission propulsion requires a deep analysis, not only from the CO_2 emission reduction potential standpoint, but also in terms of the infrastructure and energy provision. This is critical for isolated systems that are moving towards the objectives of climate neutrality and energy sovereignty from a totally different position. Figure 7 clearly exemplifies this statement, describing the percentage of energy self-sufficiency as function of the RE and EES capacity deployment requirements. Starting from situations with a large fossil fuel dependency, the penetration of non-dispatchable RE sources is very effective to reduce the contribution of fossil fuel-fired power plants and remove ICEV vehicles from the road. However, the entire replacement of technologies or processes that use fossil fuels with electrically-powered equivalents turns into a titanic effort. The significant increase of the energy demand would require up to 6 GW and 12 GWh of RE and EES capacities, respectively.

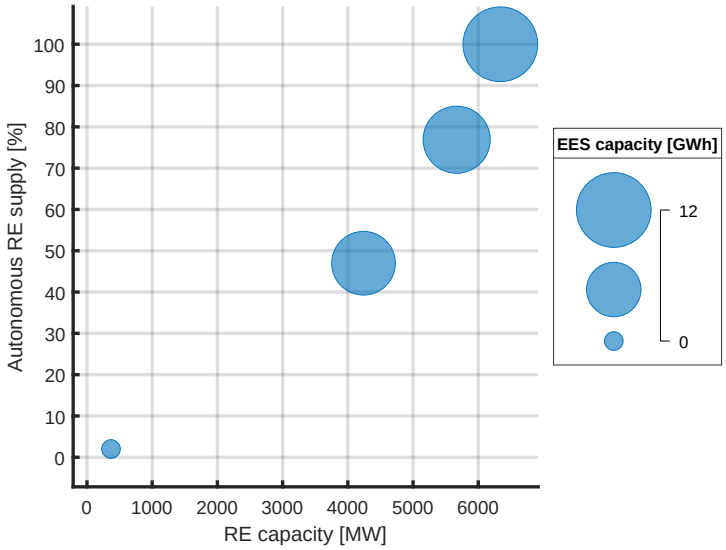


Figure 7. Percentage of energy autonomy as a function of the RE and EES capacity.

Besides the associated costs, deploying this level of infrastructure requires a considerable time frame. If 2050 is set as a reference, aligned with EU goals, if an up-to-date structure is taken as starting point, and, assuming an acceleration of capacity installation in the next decades, the annual penetration level should follow the trends included in Figure 8. However, current access and connection permits, which provide an approximate figure of

oncoming new RE capacity, are 330 MW [68]. Although relevant (current RE capacity in the island is 333 MW), this figure is well below the required rate.

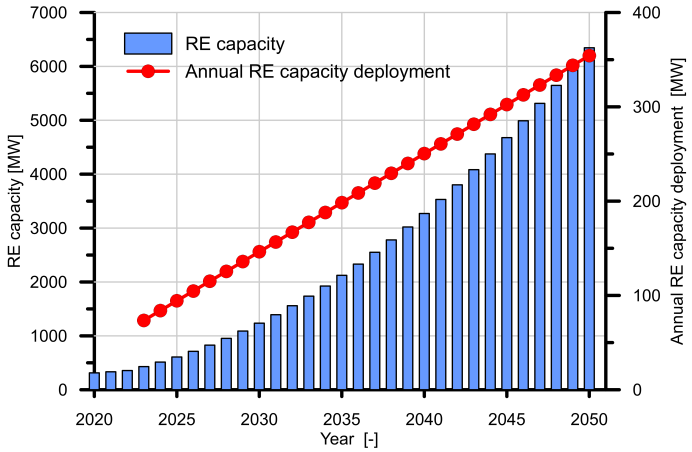


Figure 8. RE capacity deployment rate in the 2025–2050 time frame to reach decarbonisation with a fully autonomous RE supply.

5. Conclusions and Policy Implications

This paper explores a 100% renewable energy supply scenario for both power-generation and road transport sectors in the island of Tenerife. Representative of medium isolated energy systems, Tenerife island represents an excellent test case as both methodology and results can be completely transferable to the rest of isolated systems worldwide.

The island's energy system was modelled in EnergyPLAN, and validated against published data obtained from official governmental sources. Starting from the reference scenario and taking into account the current renewable technology roadmap, the impact of a full deployment of zero-tailpipe-emission vehicles on the energy system was evaluated under the consideration of an autonomous renewable energy supply.

Autonomous decarbonisation of the power-generation sectors implies a large deployment of renewable power capacity. The characteristics of these highly variable technologies, together with the nature of an isolated system, turn into high levels of curtailment (above 27%), even when considering energy storage systems. A significant back-up energy provided by dispatchable gen-sets fed by H_2 will be required to cover demand during renewable intermittency events. The internal H_2 production via electrolysis requires significant capacities that exhibit low equivalent hours of operation.

The impact of a complete technology shift in the transport sector (light- and heavy-duty) was analysed in detail. To accommodate the additional energy demand, the renewable capacity must experience a significant growth (more than 30%), requiring additional storage capacity to avoid excessive curtailment. Although the presence of V2G functionality in 30% of the light-duty fleet allows a slight reduction of the required back-up energy, the same deployment of renewable and energy storage sources is required. The analysis of the heavy-duty fleet reveals that large H_2 shares are beneficial for the energy system, as electrolysers' dispatch approach prioritises events of high availability of renewable energy. This behaviour eventually allows reducing the power and storage capacity to be installed.

In light of this, several recommendations to policy makers could be suggested:

- Energy demand reduction as a first objective. Although the results evince that a full autonomous energy supply is possible, the amount of RE to be deployed is massive. This results in a significant amount of electrical energy spilled and large EES capacities, which might put the profitability of the RE producers at risk.
- Dispatchable RE sources must be prioritised. Given the space constraints of the island, high enthalpy geothermal resources arise as the main opportunity on the island, which

require government boosting in terms of economic support during exploration and future exploitation (if it exists).

- The use of imported energy vectors to support internal demands. In this context, energy carriers such as drop-in fuels could play a key role in transportation. Their high energy density and the fact that can be used with existing technologies and infrastructure make these renewable fuels an excellent option to reduce the RE and ES requirements on the island. Without a doubt, the viability of this route must be studied in depth and it will eventually depend on how the power-to-fuel process maturity evolves.

Future research work includes a deeper analysis of different paths to reach decarbonisation on the island. Energy demand reductions in specific sectors and the comparison of additional scenarios that consider a partial dependence on energy vectors for transportation and/or power-generation will be evaluated. Every solution, to be optimised, must be quantified in terms of economic costs, deployment feasibility, and CO_2 abatement effectiveness.

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Abbreviations

The following abbreviations are used in this manuscript:

BEV	Battery electrical vehicle
E_D	Diesel energy consumption
E_P	Petrol energy consumption
$Elec_{LDV}$	Electric demand of the light-duty vehicle fleet
$Elec_{HDV}$	Electric demand of heavy-duty fleet
EES	Electrical Energy Storage
EV	Electric vehicle
FCEV	Fuel Cell Electric Vehicle
G2V	Grid To Vehicle
HD	Heavy duty
HDV	Heavy-duty vehicle
H_{2HDV}	Hydrogen demand of heavy-duty fleet
HFO	Heavy fuel oil
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
LDV	Light-duty vehicle
PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy system
V2G	Vehicle To Grid
WE	Wind energy
η_{ICE_P}	Petrol Internal Combustion Engine Efficiency
η_{ICE_D}	Diesel Internal Combustion Engine Efficiency
$\eta_{Charging}$	Charging efficiency
η_{EV}	Electric Vehicle Efficiency
η_{Trans}	Transport Efficiency

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