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Energy transition process and community engagement on geographic islands: The case of Culatra Island (Ria Formosa, Portugal)

A. Pacheco [a, *], J. Monteiro [b], J. Santos [c], C. Sequeira [a], J. Nunes [d]

[a] MORE-CIMA/Universidade do Algarve, Edifício 7, Campus de Gambelas Faro, 8005-139, Portugal
[b] ISE, Universidade do Algarve, 8005-139, Portugal & INESC-ID, Lisbon, Portugal
[c] ISE, Universidade do Algarve, 8005-139, Portugal
[d] miB, Make it Better, Association for Innovation & Social Economy, Bairro Novo da Bica, Edifício da Pré-Primária, 7940-104, Cuba, Portugal

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ABSTRACT

Islands have the potential to be precursors in the transition to clean energy, by adopting new technologies and applying innovative solutions that can serve as showcases at an international level. This paper is a contribution towards understating the importance of community engagement on energy transition processes. It covers multiple aspects of a green transition process, including technical, environmental, social, and economic issues. Starting by a participatory diagnosis process, the community of a small island located in Portugal (Culatra Island, Algarve), was challenged to lead the transition process and define different pillars of energy transition. The process brought together local authorities, academia, citizens and companies. Using practical examples, it is shown how the community is succeeding in tailoring new technological solutions for a green transition, according with the specific needs of the island, as expressed by the islanders themselves, including batteries, electric vehicles, retrofitting of homes, or heat pumps, which, when combined, could lay the foundations for the creation of a Renewable Energy Community and leverage socioeconomic benefits.

1. Introduction

The Paris Agreement [1] recognizes that islands are particularly vulnerable to climate change and are highly dependent on fossil fuels and energy imports. Being small isolated systems, islands face a set of energy challenges related to their specific geographic and climatic conditions and have the potential to be precursors in the transition to clean energy by adopting new technologies and applying innovative solutions [2].

In recent years, several studies have focused on the integration of renewable energy sources (RES) in islands [3], in particular on the utilization of energy storage and demand side management solutions in smart energy islands, including the solutions that allow flexibility and sector coupling. In the scope of demand side management and sector coupling, all the reviewed solutions, besides increasing the capability of the grid to host RES, also enabled a reduction of the surplus of the electricity produced by those sources.

Other approaches presented achieve full energy independency of Reunion Island, by 2030, using 100% renewable energy [4]. In order to avoid a high intermittency, the authors established that the produced energy, while relying on 100% from RES, may include around 50% of intermittent sources at some periods, if compensated with suitable storage techniques and Demand Response (DR) solutions.

Supported on the fact that the cost of battery systems is decreasing, making them economically viable in a few years, another study focused on examining pathways for the transition of small islands from fossil-based fuels to RES [5]. A 2-phase pathway is considered. In the first phase, until 2030, a 30% integration of intermittent RES with battery storage systems is defined, and in the second phase, from 2030 to 2055, the rest of the conventional sources will be replaced by more RES, complemented with the sufficient long-term storage, taking advantage of the lower price of storage systems.

A policy-driven approach is performed in the energy transition process of the Hawaii Island [6]. Besides combining RES with single battery storage systems, the study also considers the vehicle-to-grid (V2G) technology as a solution to develop the future smart

* Corresponding author.
E-mail addresses: jmmontei@ualg.pt (A. Pacheco), jmmontei@ualg.pt (J. Monteiro), jnsantos@ualg.pt (J. Santos), cdsequeira@ualg.pt (C. Sequeira), jose.nunes@makeitbetter.pt (J. Nunes).

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grid of the island. Although the scarce existence of electric vehicles in remote islands normally means that it can rarely be applied to insular situations, there is another potential bidirectional energy transfer mechanism that reuses the concept of V2G, which relies in electric boats, and associated batteries [7,8]. An example of a real-time load-support system with a bidirectional energy transfer mechanism with electric boats, battery storage systems and community generators adjusts the customers RES demand, the available electric boats, and the battery storage system to provide efficient load support [8]. Another case study evaluated how the electrification of ferryboats can offer several advantages in the framework of 100% renewable smart islands [9], where the excess of energy produced by RES is used to supply the electric boats that cross between the island and the mainland.

In fact, the excess of energy produced at some time instants may be used in many other applications beyond those that are commonly considered. In 1964, the first plant of sea water desalination of Europe was built, more specifically in Lanzarote Island, Spain [10], to supply a desalination system. The assessment was made for two islands of the Canary Archipelago, where a hybrid (solar and wind) renewable energy system was used to supply the power requirements of an autonomous desalination system with a capacity of up to 50 m^3 of daily production.

But energy transition processes are complex processes, facing many challenges which extend much beyond the technical issues discussed previously. Traditional energy transition processes commonly start by the design of an appropriate technical solution, that is then followed by meetings with the communities to inform and consult them. In fact, most studies that centre the attentions on insular sustainable transition are so focused in producing the sufficient energy to satisfy the needs of the island as a whole that they forget the involvement of the community. This leads to tensions between stakeholders involved in energy planning and, at times, community opposition to energy plans [11]. This happens because the 'NIMBY' (Not in My Backyard) hypothesis, that posits that although people, according to some opinion polls, tend to support RES projects in general, they are likely to oppose specific project plans in their local area for self-interest and particularistic reasons [12]. As such, several stakeholders, working in the field of energy research and policy, agree that energy transitions must be led by transdisciplinary consortiums, guided by social science concerns around the human dimensions of energy [13]. These methods are key to achieve public acceptability of green energy solutions by members of a social unit [14,15].

The success achieved on energy transition processes throughout islands [16] revealed how those territories are not only distinct places in which regards topography, location in global value chains, but are associated with a form of social realm centred on the community. As such, on the contrary of what is perceived to happen on traditional communities, the actors who promote smart energy innovation on islands emphasize how keen local actors are to learn, cooperate and engage to promote new energy technologies. Some studies have considered the involvement of the community in the energy transition process, as for instance in the Tilos Island [18], where, based on the participation of the residents, sustainable energy models were promoted with the aim of increasing energy autonomy. Of interest was the utilization of a Quadruple Helix's (QH) strategy involving the union of four components - government, industry, society, and academia - that has shown to accelerate innovation, support regional growth and the transfer of research. The authors also point out that the most important mission of the QH strategy was to provide a sustainable energy culture to the community, which leads to better energy management. As they stated, the transition of the energy sector to a more sustainable one is a technical issue that involves critical societal aspects [18]. In fact, energy is associated with many areas of sustainability, as it can support sustainable transportation and sustainable desalinization of water, among others.

Under the scope of the Clean Energy for EU Islands Programme (CE4EU), local communities are being challenged to search for a stronger control over their traditional activities, overcoming external factors driving high costs of energy supply and production. As such, six pilot islands were challenged to develop each own "Island Clean Energy Transition Agenda", a strategic roadmap for the transition process towards clean energy. One of those islands is Culatra, a small island located in Algarve, Portugal. Nested in the barrier islands that compose the Ria Formosa Natural Park, Culatra is one of those rare examples of genuine community resilience that has overcome all sorts of challenges since first fisherman settled on the island 150 years ago. From an uncertain legal status to the environmental constraints of being within a natural protected area, and the socio-economic difficulties due to its physical and social isolation, Culatra faces specific challenges in terms of energy efficiency and self-sufficiency, water scarcity, waste management and localised pollution. Given that energy accounts for some 50% of household expenditure on the island, energy poverty is another important challenge.

While embarking on its initiative, the Culatra community has taken up lessons from successful cases of energy transition in other islands – for example, in Norway and Denmark [16,17]. The lessons that inspired Culatra' community were mostly those showing that success depends on specific virtuous configurations of technologies, humans, organisations and space in their specific contexts, beyond the energy issues they are actually seeking to address.

The main contribution of this work is to show how an energy transition process can successfully be implemented if it includes (1) a community participatory diagnosis process, (2) a strong cooperation between citizens, authorities, researchers and companies, (3) a wide evaluation and combination of all potential technology pathways, including batteries, electric vehicles, retrofitting of homes, or heat pumps, which, when combined, could lay the foundations for the creation of a Renewable Energy Community. The paper is organized in the following structure: section 2 presents the study area, including the natural reserve where the Culatra Island is nested; section 3 presents the Community Participatory Process implemented in the island and the main results obtained; those results are then used in section 4 which evaluates the potential of achieving the complete self-sufficiency of the island using Photovoltaic (PV) generation; section 5 discusses the results obtained and finally, section 6 presents the main conclusions of the study.

2. Study area

Culatra Island (Fig. 1) is located in the Algarve region, the southernmost region of mainland Portugal. It is one of the five barrier islands that compose the Ria Formosa Natural Park, a multi-inlet barrier island system in southern Portugal. The Ria Formosa system is unique and remarkable, and amongst the most studied coastal area of Portugal on a wide range of topics, from geomorphology and coastal dynamics to ecology, biodiversity, economy and social values. Ria Formosa was legally constituted as a Natural Reserve in 1978 and as a Natural Park in 1987, being considered one of the most important areas for nature conservation in Portugal. The barrier system is extremely dynamic, which has been related to tidal inlet evolution, shoreline evolution, longshore drift, overwash processes, dune formation, backbarrier processes and artificial sediment nourishment actions [19].

Culatra Island is about 7 km in length and has a maximum width of 1.2 km, comprising a total area of 4.34 km^2. The island is

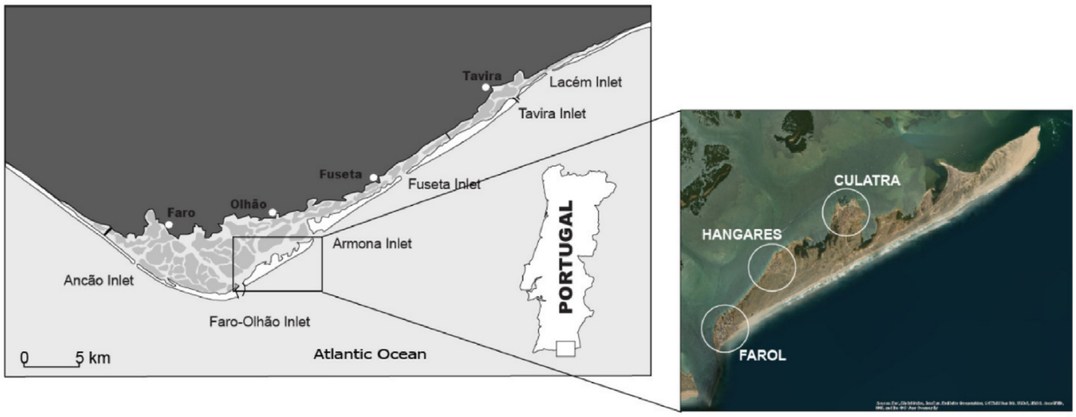

Fig. 1. Situation of Culatra Island (36.9937°N; −7.839793-W) in the Atlantic Ocean. (Source: CULATRA 2030 – Sustainable Energy Island). There are three settlements: Culatra (focus of the paper), Hangares and Farol.

permanently inhabited by around 1000 people. The main economic activities on Culatra are fishing and tourism, both of which are highly linked to Ria Formosa. The natural reserve is the most productive aquaculture zone in Portugal, representing about 41% of the Portuguese production [20]. The resources of the lagoon system are an important source of income for a large part of the population living in the Ria Formosa area, especially for the Culatra Island residents, where the vast majority of the economic income is related to mollusc farming or fishing. While the fishing activities have economic movement all year, the economic activities driven from tourism are characterized by their seasonality. In the high season from June to August, the population on the island triples compared to the permanent population. The island furthermore sees a minor raise in population during the midseason from April–May and September–October.

The citizen engagement is, historically, strongly present on the island since the very beginning of the community's establishment. The housing settlement of Culatra Village dates from the 16th century, as a seasonal movement of people who came to work in the sardine fishing communities. Due to the abundance of fish, shellfish and the amenity of the waters of the Ria Formosa Natural Park, some families decided to settle, building temporary housing. After these first settlements, an increased migration to Culatra Village took place, which implied the progressive multiplication of housing. Because of the territorial isolation, social isolation was much more pronounced, and the community was not part of the general improvement in living conditions that, over time, was created inland by the central and local administration. Faced with these constraints, the community engaged in collective actions to meet their basic needs, such as electricity (grid connection in 1998), drinking water/sanitation (in 2010), education, health, urban planning, among others.

3. Methodology

3.1. The Community Participatory Process

The energy transition process of the Culatra Island is included in a broader scope, involving several topics of sustainability. The whole process was started by a Community Participatory Process, where islanders and institutions were invited to collaborate to help specify the set of solutions that will reduce the human footprint in the island. In the following we describe that process and the results obtained by it.

Envisaging the general territorial sustainability and valorisation, the first concern was to understand and circumscribe the main constraining forces, but as well opportunities, generated by the legal frame in which the island and its fishing communities are settled. Among all, the environmental barriers showed to be the major challenge for the whole transition process; Culatra Island is within the Natural Park of Ria Formosa (PNRF). However, when assessing the opportunities, a new prospect for requalification emerged in 2018 when the Portuguese Government officially recognized the Culatra Village as a consolidated fishing residential nucleus (Ordinance No. 277-B/2018). This statute values the historical roots of the fishing settlement, with clear evidence of ancient occupation and, therefore, has a social, economic and cultural significance worthy of recognition and ratification. This fact made it possible to apply for housing licences in a very particular context (within public water domain) valid for the next 30 years, eventually renewable if the identity of the fishing village and inhabitants is maintained.

Originally framed under the CE4EU, the energy transition process in Culatra Island was developed in accordance to a focal governance tool - the Clean Energy Transition Agenda (CETA). The planning, preparation and implementation of the CETA implies a large-scale mobilisation of the distinctive sectors on a QH scheme - communities, academia, authorities, companies - that support and regulate the development of the island and of its communities. Using this QH model, different pillars of energy transition were defined collectively by key stakeholder groups, comprising members from academia, companies, residents' groups and administration. The Community Participatory Diagnosis (CPD) was carried out in three distinct phases (Fig. 2): Phase1 - Views: understanding the actors and the territory as a social product; Phase 2 - Horizons: dialogue and proposals for action; and Phase 3 - Negotiation and Action: seeking consensus for the development of the territory. During this dynamic process, possible transition pathways were discussed and agreed upon to create a shared vision for the future development of the island, where proposals for actions were generated collectively; particularly several energy generation options for the public infrastructure, which can then be further utilised for resident housing. Opportunities for cooperation and financing were also identified.

3.2. Driving the action towards energy transition

Following the implementation of the three phases of the CPD described on sub section 3.1, five pillars supporting the transition process emerged: (1) Electricity generation, storage and

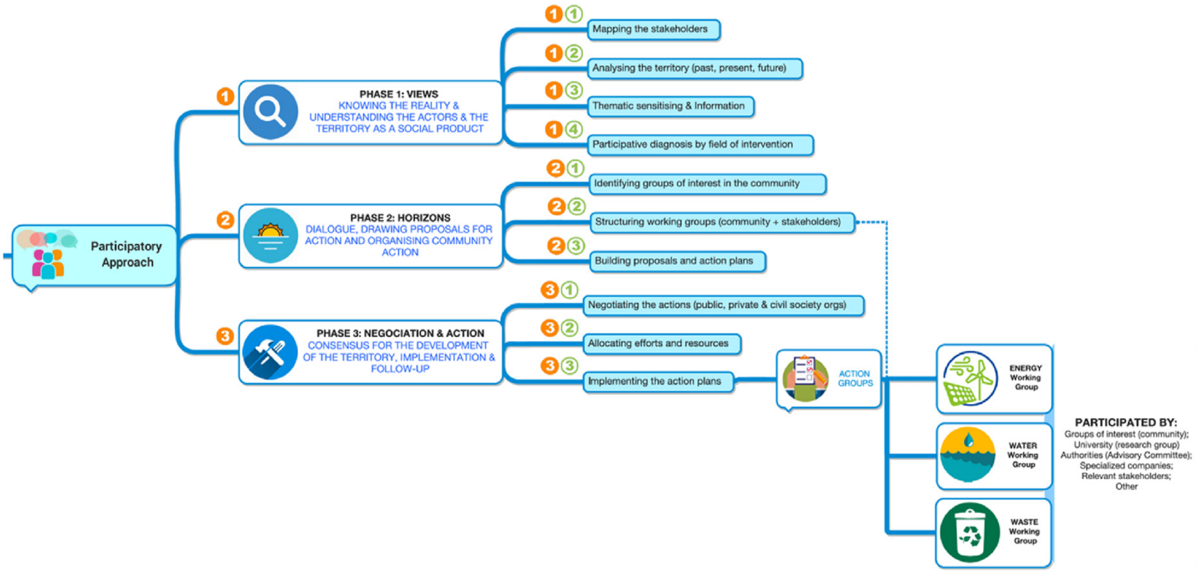

Fig. 2. Phases and main goals of the Community Participatory Diagnosis (CPD) based on a quadruple helix's (QH) scheme.

distribution; (2) Housing and building efficiency; (3) Transportation (on the island; to and from the island); (4) Water supply and treatment; and (5) Waste management and valorisation. The CPD lead to the definition of objectives for each of the pillars (Table 1), which allowed the community to further individualise strategies and actions in interdependent energy-related areas. As such, the participatory approach includes cross-sectoral integration where decisions for one pillar influence the other pillars.

In the field of "Electricity generation, storage and distribution", Pillar 1, the objective that resulted from the CPD process was to achieve complete self-sufficiency of the island in terms of electricity supply, based on solar PV, battery storage and smart grid control, including DR. This objective was set to be achieved by 2030 and led to the development of a set of projects on solar PV plants to enable the required generation. This also requires storage solutions, such as batteries, and smart-grid technologies, to allow the control of electrical loads and resulting in a higher correlation between consumption and generation profiles. The solar PV plants are to be introduced to the electrical grid of the island with a community focus, and not as individual solutions, to supply most of the electricity demand on Culatra Village.

The amount of solar PV generation to be installed until 2030 must not only reflect the daily consumption profile of the island, but also the future requirements imposed by the other pillars, as it is foreseen an increment of consumption due to the effect of electrification in transportations to/from the island, for fishing, aquaculture and tourism, energy in buildings, water supply and waste management. As such, the foreseen energy transition project involves the installation of several rooftop PV plants on the Culatra Village' public infrastructure: the warehouses for fishermen and auxiliary structures, the sport/local community centre, the primary school, the social centre, the church and the shaded walkways (Fig. 3A), divided into 3 major sectors: the North sector (Fig. 3B); the West sector (Fig. 3C) and the Central/South sector (Fig. 3D and E).

The West sector is composed of a church and some shaded walkways (Fig. 3B). As for the church, only the roof section facing south was used. The modules follow the inclination and orientation of the roofs. They were distributed taking into account the shadow created by the church tower on the roof. In the case of the shaded walkways, modules will be installed in the horizontal plane. The building structures in the North sector are composed of warehouses (Fig. 3C) that support local fishermen. There is a cluster of small warehouses (Fig. 3C – big yellow rectangle) that are going to be rebuilt with flat roofs. Therefore, in order to optimize the available surface as well as adjust the production curve to match the consumption profile, a double orientation (East/West) was chosen for all of the flat roofs. The Central/South sector is composed by three different types of buildings: a sports/local community centre, a primary school and the social centre (Fig. 3D). In all of these buildings, modules will be installed following the inclination and orientation of the roofs. In the primary school, a sunshield will also be built (Fig. 3E).

Table 1
Pillars and objectives proposed for the island transition process led by the community.

	Pillar	Objective
1	Electricity generation, storage and distribution	Implement a self-sufficient electricity supply system based on solar photovoltaic, battery storage technologies and smart grid distribution
2	Transportation (to and from the island and on the island)	Decarbonise the island's transport system by focusing on the socio-economic activities and solar-electric mobility
3	Housing acclimatization and public building efficiency	Eliminate energy poverty by increase the energy efficiency and energy generation capability of buildings
4	Water supply and treatment	Produce water for self-consumption using desalinization processes and implement water management initiatives
5	Waste management and valorisation	Use island sustainability as a pillar for transition, creating an example of global change in the community's lifestyle

Fig. 3. (A) Location of the foreseen PV power plant in the Island of Culatra (source: Google Earth); (B)3D model detail on the PV application on the West; (C) 3D model detail on the PV application on the North Sector; (D) 3D model detail on the PV application on the Centre/South Sector; (E) 3D model detail of the primary school, where a sunshield will also be built.

3.3. Cost benefit analysis

After dimensioning the PV power plant, the following objective was to attempt to provide a high-level analysis of the generation of the PV plant versus the consumption of the island. The PV generation profile was obtained with PVSyst software and is the same that was used for the Long Term Yield Assessment (LTYA), albeit with a few differences as the profile extracted from PVSyst in the LTYA undergoes further data treatment (e.g. irradiation data, availability losses, etc.). The quarter-hourly electricity consumption profile refers to the year of 2019 and was shared by the distribution system operator (DSO). This profile was adapted to hourly averages in order to be comparable with the profile generated from PVSyst. Different meteorological data sources were considered for the LTYA study and full details can be consulted on [21].

Besides the consumption of the island, the analysis focused on evaluating six parameters: (1) Grid to Culatra (kW), which refers to the grid electricity that is consumed at the Culatra Fishing Village; (2) PV to Culatra (kW), which refers to the amount of energy generated by (all sectors of the) PV plants that is consumed by the village; (3) PV to grid (kW), which expresses the excess electricity produced by the PV plants that is above the villages' demand and thus is injected into the public grid; (4) Self Consumption Ratio (SCR in %), a measure of the ratio between the photovoltaic energy that is auto-consumed and the amount of PV energy that is generated in the village; (5) Self Sufficiency Ratio (SSR in %), a measure of the ratio between the PV energy that is auto-consumed and the total amount of energy that is consumed in the village; and (6) the Internal Rate of Return (IRR in %), an estimation of the profitability of the investment in the PV system that makes the net present value (NPV) of all cash flows equal to zero.

4. Results

The CPD proved essential for defining priorities and generating ideas for actions with a high degree of commitment by all local actors. It also helped bring about important changes in mentality among islanders, boosting their confidence and sense of self-belief. An overview of the integrated future scenarios for the Culatra energy system is illustrated in Fig. 4. As an outcome of the CPD, and in straight alignment with the legal background of the Culatra Village (currently in the process of obtaining permits for housing in the public water domain), it became clear the need for (1) creating conditions for the installation of a pilot unit of production and distribution of solar energy (to demonstrate the potentialities and adapting the consumption to the generation), which can be managed by and constitute an asset of the community; (2) reuse the infrastructure, constructions and resources available in the community, avoiding excessive costs, negative social and environmental impacts and complying with current regulations; and (3) create the conditions for the development and implementation of self-funding measures, aiming to support the energy transition and the general sustainability of the island communities. Synergistically, this would represent a potential opportunity not only to requalify the urban area of Culatra Village without conflicting with the environmental and administrative regulations in place, but as well to accomplish with the main priorities set by the community under the CPD.

Table 2 summarizes the CPD results in terms of energy and shows the alignment between the problems identified by the community and the base line in which the energy transition was set; the results of energy consumption and CO_2 emissions for the island are shown in Table 3. One of the outcomes that resulted from the CPD process was the need to achieve the complete self-sufficiency of the island in terms of electricity supply, based on solar PV, until 2030. This objective must be met in several phases. In the first phase, the amount of solar PV generation must reflect the daily consumption profile of the island. In parallel with this initial phase, an increase in the consumption profile of the island will likely occur because of the electrification in transportations (to/from the island, for fishing, aquaculture and tourism) and the integration of all the pillars show in Table 1. The generation required for that second phase was based on the island consumption profile. The DSO (E-Redes, former EDP Distribuição) supplied data from 316 smart meters installed on the island, which allowed dimensioning the solar PV system shown in Fig. 3.

According to the supplied data from the DSO, the largest energy sector on the island is the heating sector, which consumes 8640 MWh/year, nearly 54% of the entire energy consumed on Culatra Village (Table 3). The heating on the island mainly happens during the winter and consists of electric heating and heat pumps. There is little-to-no cooling present on the island. The majority of the houses are simple constructions that are not properly isolated and as most of the residents are fishermen, with fluctuating and lower income, energy poverty is a reality, with a high percentage of the electricity bill used to heat each house.

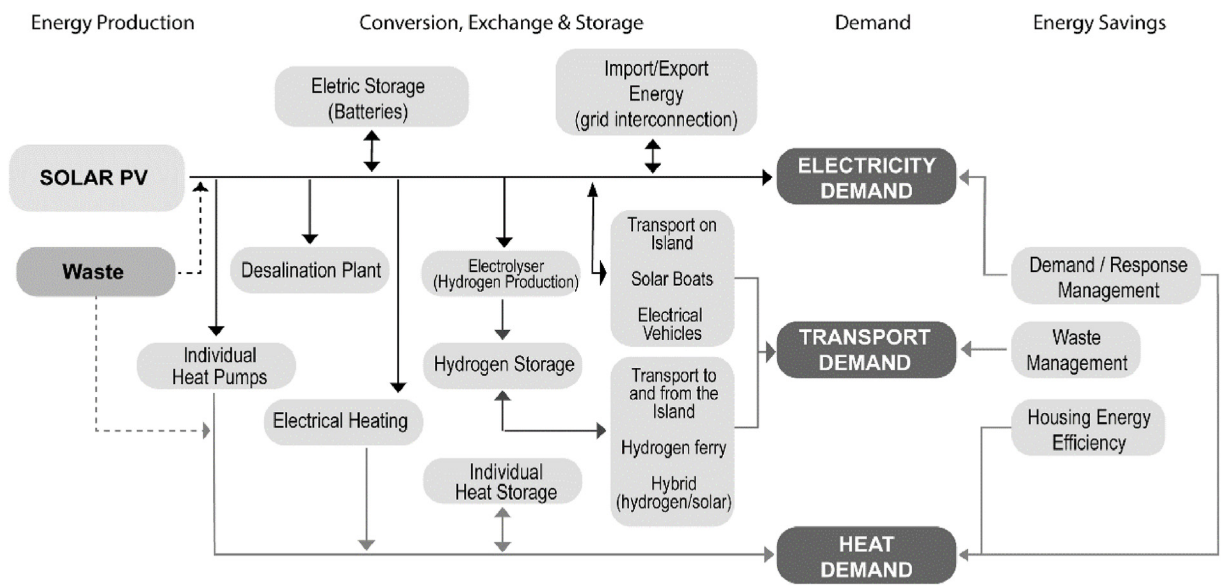

Fig. 4. Transition pathways for Culatra's energy transition, product of the Community Participatory Diagnosis (CPD).

Table 2
Main results of the Community Participatory Diagnosis (CPD). Problems and needs identified and prioritized by the groups (community; civil society; companies/private sector) and respective proposals for mitigation.

Priority	Problem & Needs	Alternatives & solutions
1	High energy cost (representing ≈40% of the household costs)	Energy tariff negotiation, highlighting the need to create conditions with the DSO to establish a Sustainable Energy Community for the management and negotiation of tariffs.
2	Lack of use/wasting of renewable energy sources	Installing solar panels in public infrastructures for a new energy production & distribution system, which could be financed by social economy initiatives.
3	Household consumption management	Organize awareness-raising and capacity building actions on how to produce, use and save energy for the population and agents.
4	Poor technical conditions of energy distribution	In parallel to energy self-sustainability measures, proposing to the grid operator the cable replacement due to its aging and malfunctions.
5	Frequent power cuts	Start producing energy in the island. Eliminate the need for using the diesel generator (pollutant: combustion gas emitter, noise, visual/landscape).
7	Electric mobility	Promoting the use and purchasing of electric vehicles, substituting all the existing ones working with fuel/diesel; Introduce circular economy and shared economy practices in the island transportation system; Introducing solar boats, both for leisure, economical activities and public transportation to the island.

Table 3
Estimate of the final energy consumption in MWh and the calculated CO2 emissions in tCO_2, eq on Culatra in 2019 (includes the three inhabitant villages: Culatra, Hangares and Farol).

Data for year 2019	Final energy consumption	CO_2 emissions
	[MWh]	[$tCO_{2,eq}$]
Electricity consumption		
Residential	2079	767
Primary sector	1039	383
Industries	0	0
Tertiary sector	159	59
Transport on the island		
Vehicles, diesel	31	8
Vehicles, gasoline	85	21
Transport to and from the island		
Maritime transport, diesel	317	85
Maritime transport, gasoline	3799	946
Heating fuels		
Gas	610	123
Diesel/Gasoline	8036	2000
Total	**16,149**	**4392**

The second largest sector is the transport to and from the island, with 4116 MWh/year (~25%).public transportation is possible via a passenger ferry from Olhão and Faro to Culatra Village and Farol. Ferries operate four times during the winter and eight times during the summer season and are all diesel fuelled. Also, many people on the island have their own private maritime transport to get to and from the island. Electricity for other uses (besides heating) is the third sector with 3277 MWh/year (~20%); the smallest sector is the transportation on the island which only makes up 1% of the total energy consumed, since the transport on the island is highly affected by the fact that there are no paved roads on Culatra Village. As such, the transportation sector on the island only counts few vehicles such as tractors and motor tricycles to carry goods and to assist residents with reduced mobility. All vehicles on the island are powered by fossil fuels.

It is important to mention that Culatra Island, as part of summer destination, has an impactful variation in seasonal energy consumption. During the year of 2019, the Culatra Village consumed a total of 1181 MWh. The energy consumption was higher in summer months and lower in winter (Fig. 5A) and was nearly constant for distinct days of the week (Fig. 5B). Overall, in summer months the electrical consumption is 49.7% higher than in winter months. As such, the increase of the self-sufficiency of the island in terms of electric energy requires the analysis of the consumption profile of the island.

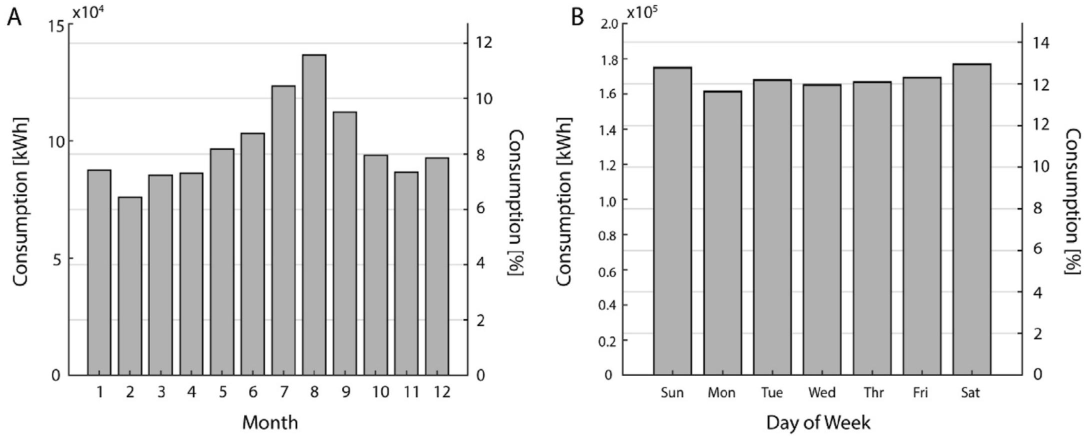

Fig. 5. (A) Monthly energy consumption of the Culatra habitational nucleus; (B) Weekly energy consumption of the Culatra habitational nucleus (data provided by the DSO).

The residential sector consumes the highest ratio of the electrical consumption of the island, with nearly 63.4% of the whole consumption. The second major consumption level results from the fisherman activities (primary sector), which represents nearly 31.7% of the whole electrical consumption of the island. The tertiary sector represents nearly 4.9% of the consumption, most of it associated with restaurants, grocery stores and local services.

In terms of power consumption during the day (Fig. 6A), the Culatra Village always consumes more power at the end of the day, but has a less pronounced maximum in consumption between 10 a.m. and 3 p.m. During the night, the minimum consumption level varies between 80 kW in winter (herein represented by February 2019, Figs. 6B) and 125 kW in summer (herein represented by August 2019, Fig. 6C). The results that emerged from the analysis of the consumption profile are mandatory to specify a set of solutions capable of increasing the self-sufficiency of the island.

The overall layout of the PV power plant was designed to optimize surface use and electricity generation output (Table 4) by taking into consideration the consumption profile. The aim of the project, in this stage, was to increase the IRR, with the investment being recouped by the tariff rates paid by the consumers. As such, the combined analysis of these requirements led to the proposed installation of 859 standard monocrystalline PV modules, each with a peak power of 360 Wp. A Performance Ratio (PR) of 81.9% was estimated at the beginning of the project. Annually, this PR was also reduced, considering both a light induced degradation and an annual degradation rate. The light induced degradation was estimated at −1.3% for monocrystalline silicon modules and the annual degradation was estimated at 0.5%/year for crystalline silicon modules.

The SCR presented on Table 5 show that, on average, 85.7% of the energy produced in the island is auto consumed. This average is penalized by the months of March, April and May, which show SCR's lower than 80%, while it reaches nearly 100% in August and December. During summer, PV production increases and so does the electricity demand on the island due to tourism and seasonal occupation. The remaining 14.4% of the energy produced is injected in the public grid. By selling this energy to the National grid, instead

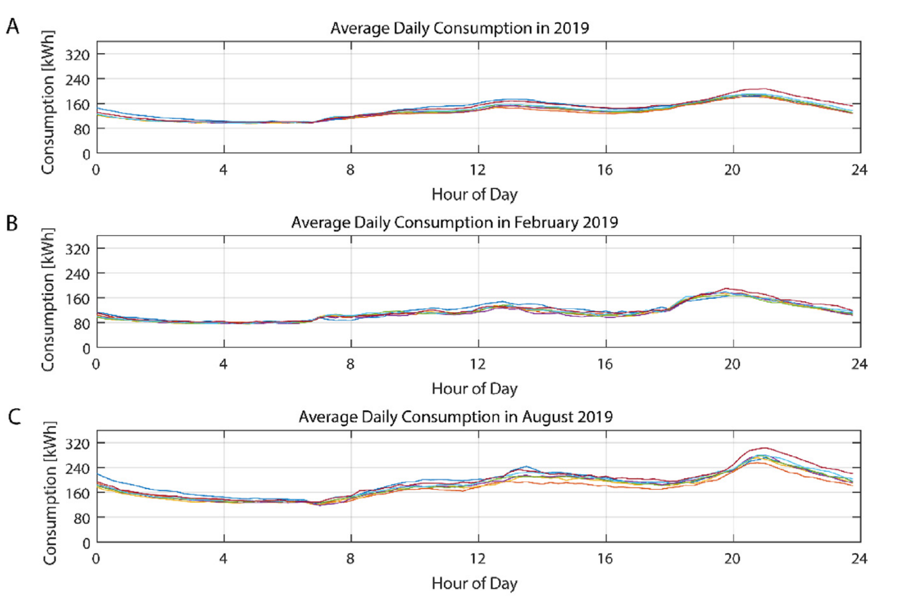

Fig. 6. Daily average power consumed in the Culatra habitational nucleus during (A) the year of 2019; (B) the winter, herein represented by February 2019; (C) the summer, herein represented by August 2019.

Table 4
Specifications of the photovoltaic plants in each sector balancing generation/consumption.

	North Sector		West Sector		Central/South Sector			
	Warehouse – cluster	Warehouse – big	Church	Walkways	Sports/Community Center	Primary School	Social Center	Unit
System size	104.40	20.16	10.44	77.76	38.52	39.60	18.36	kWp
N°. of modules	290	56	29	216	107	110	51	pcs
Type of modules	Mono crystalline - 360 Wp							
N°. of inverters	8	1	1	3	1	17	1	pcs
Type of inverters	String inverter							
Power of Inverter	13.2	20.0	13.2	20.0	36.0	36.0	20.0	kW
N° of mod/string	17 & 3	14	18 & 11	18	14 & 17 & 14	20 & 15	17	pcs
N° of string/inv	8 & 3	12	1	12	2 & 3 & 2	4 & 2	3	pcs
DC/AC ratio	0.8	1.3	0	1.3	1.07	1.1	0.92	
Modules tilt	23 & 7	0	23 & 7	0	12	12	32	0
Modules azimuth	182	0	182	0	274 & 183 & 94	183	188	° (0–360)
Typology	Inclined	Flat	Inclined	Flat	Inclined			Unit

Table 5
Monthly comparison between generation/consumption (consumption profile provided by the DSO).

Month	Culatra Consumption (kWh)	PV plant total production (kWh)	Grid to Culatra (kWh)	PV to Culatra (kWh)	PV to Grid (kWh)	SCR - Self Consumption Ratio (%)	SSR - Self Sufficiency Ratio (%)
January	87,707	23,277	66,557	21,157	2127	90.9	24.1
February	75,867	26,647	53,992	21,881	4772	82.1	28.8
March	85,471	38,989	55,285	30,191	8804	77.4	35.3
April	86,323	48,159	50,493	35,836	12,328	74.4	41.5
May	96,585	56,005	54,417	42,173	13,837	75.3	43.7
June	103,299	57,410	56,091	47,212	10,202	82.2	45.7
July	123,391	59,184	70,275	53,120	6068	89.8	43.1
August	136,770	53,746	84,672	52,102	1648	96.9	38.1
September	112,301	43,355	72,416	39,890	3470	92.0	35.5
October	93,763	33,146	64,345	29,424	3728	88.8	31.4
November	86,745	23,822	65,151	21,600	2228	90.7	24.9
December	92,558	20,645	72,230	20,335	317	98.5	22.0
Year	**1,180,780**	**484,384**	**765,925**	**414,921**	**69,529**	**85.7**	**35.1**

of selling it to the consumers, a lower economic income is obtained. As such, it is clear that, while the SSR shows that the proposed installation reduces the dependency on energy imports in 35.1%, installing more solar generation, if not complemented with other storage solutions or demand/response actions, will not bring a proportional economic benefit.

This is further supported when analyzing Fig. 7A and B that respectively represent the average consumption in February and August 2019, overlapped with the expected generation level for the corresponding months. As it can be observed, increasing the solar generation will result in an increment of power being injected in the National grid.

A simple exercise can be formulated to express the increment of the solar power generation on Culatra Village. The roof area in privately owned houses which is yet to be used is approximately 17,000 m^2. By selecting the best places for installation, in terms of inclination and orientation of the roof, 4000 m^2 of PVs cells can cover 100% of island needs. So, the existing infrastructure allows scaling the PV generation to achieve a total capacity of nearly 2500 kWp (subtracting 20% of losses as considered in Table 6). In fact, it allows generating significantly more energy than the one that is consumed at present.

Finally, the overall summary of the costs and economic benefits that the proposed PV installation will produce is given on Table 7. As

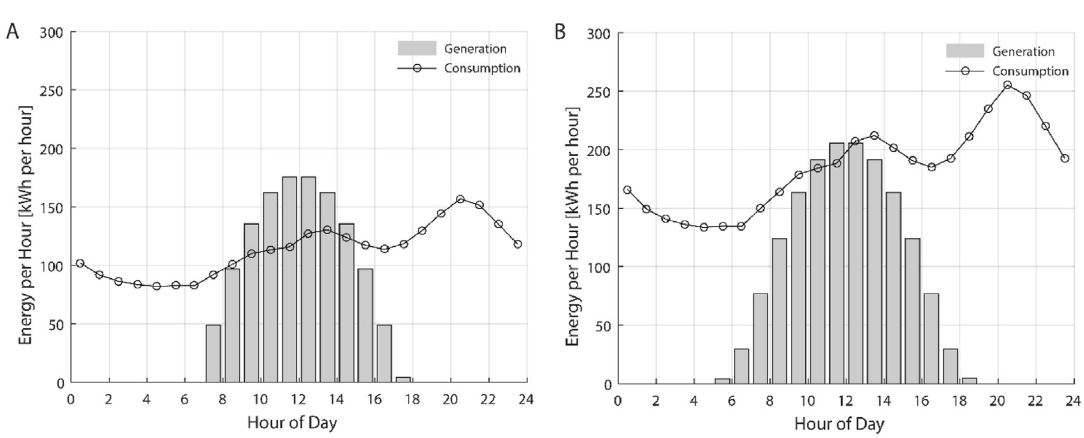

Fig. 7. (A) Average daily consumption in February 2019 versus expected generation; (B) Average daily consumption in August 2019 versus expected generation.

Table 6
Potential solar generation at private owned houses.

PV Project	PV plant	Unit
System size – 1700 m^{2}13	309	kWp
PV potential at private owned houses	**PV future plant**	**Unit**
System size – 17,000 m^2	3090	kWp
System size - 17,000 m^2	assuming 20% losses = 3090–618 = **2472**	kWp
	4200*	kWh/year

* considering 1700 h the number of solar hours per year in Culatra according solar resource maps of Portugal (https://solargis.com/maps-and-gis-data/download/europeestimated).

Table 7
Generation, costs and savings of the proposed PV installation.

Parameter	Value									
CAPEX - Capital Investment (€)	371,088									
Year	1	2	3	4	5	6	7	8	9	10
OPEX – Operational expenditures (€)	3092	3092	3092	3092	3092	3092	3092	3092	3092	3092
Annual production (MWh)	484	481	479	476	473	470	467	464	462	459
Energy Savings (MWh)	415	412	410	407	405	403	400	398	395	393
Cost savings (k€)	71,97	71,54	71,11	70,68	70,25	69,83	69,41	69,00	68,58	68,17
Injected to grid (MWh)	70	69	69	68	68	67	67	67	66	66
Grid injection revenues (€)	2851	2834	2817	2800	2783	2766	2750	2733	2717	2700
Annual cash-flow (k€)	71,72	71,28	70,83	70,39	69,94	69,51	69,07	68,64	68,21	67,78
IRR	17%									

it can be observed, the obtained IRR rate is of 17% per year. This value was determined by taking into consideration the consumption profile provided by the DSO and the information published by the price regulator in Portugal, ERSE. Given the relatively small scale of the project, and since the location is difficult to reach (material needs to arrive by boat), the Capital Expenditure Costs (CAPEX) were estimated at 1.2 Euro/Wp, resulting in a total capital investment of 371,088 €. The Operational Expenditure Costs (OPEX) were estimated at 10,000 €/MWp, which results in an annual expenditure of 3092 €. A value of 80.6% was considered for the initial performance ratio followed by a yearly degradation factor of −0.5%.

Electrical storage is an option that allows a greater usage of the energy produced on the island. The transportation sector can provide part of the required flexibility in the form of smart charging of electric and solar boats. This allows the batteries of the electric boats to be used as storage units that not only charge according with the generation curve of the island, but also feedback energy to the grid whenever necessary using vehicle-to-grid (V2G) solutions. This requires controlling the charging of the batteries when the generation surpasses the consumption and injecting part of that energy back to the grid when the consumption surpasses generation. Thus, incorporating and electrifying the transportation sector will not only help to reduce CO_2 emissions but also provide flexibility in the local electricity grid, however, this requires coordination between the production and consumption side of the local grid.

5. Discussion

As already observed on similar contexts, community renewable energy and citizens' energy needs are crucial issues on the transition paths to low-carbon energy transitions which are based on renewable-energy technologies. The CPD on energy transition implemented at Culatra was based on the QH model and evidenced the importance of transcending energy issues to include water, waste, local economy and social welfare, among others. As shown on Tilos (Greece) [18], and now reaffirmed at Culatra, the QH model is accelerating the transfer of research and innovation results to regional growth while increasing the replication potentials.

Digitalization of energy and distributed storage are shaping the future of electricity use. Microgrids represent the means by which the purpose will be achieved. Containing all the elements of complex energy systems, microgrids maintain the balance between generation and consumption, and they can operate on and/or off grid. However, microgrids installed in islands are more prone to suffer from RES intermittency and blackouts [21]. Many RES are known as intermittent resources and, thus, require complementary systems to adjust the necessary real time equilibrium between generation and consumption [22]. In order to accomplish that, there is a need to compensate the fluctuating behaviour of the solar energy. Geographical islands, such as Culatra, have been considered a challenging environment to test renewable energy integration strategies as well as cutting-edge technologies due to the alternation between actual grid-connected and island mode. Weak connections to the mainland and, subsequently, the strong changes in seasonal energy demand led to power outages and stability issues [23].

The target defined by the CPD for Culatra [24,25] was to install a set of renewable generation systems (predominantly photovoltaic) until 2030, allowing 100% of the consumption of electricity to result from RES. At this stage only part of the rooftops available in the island (public owned infrastructure) were considered, allowing the installation of 309.24 kWp, using 859 Mono crystalline PV modules of 360 Wp each. Yet the total energy generated during the year accounts for nearly 35% of the total energy consumed in the island. Even so, the results obtained have shown that in a year, nearly 14.3% of the energy generated will be injected in the national grid.

Thus, an important result emerging from the LTYA performed within our study was the need to introduce DR measures, crucial in power systems that have a high penetration of variable RES production, to absorb the excess of electricity production and to maintain system stability, which can be critical in a self-sufficient grid. DR measures were already tested at a community of domestic end-users in the island of Lampedusa (Italy), where an energy system was presented and applied for managing the aggregated daily load profiles gathered in a real measurement campaign [26]. The overgrid DR architecture was successfully used for managing the residential flexible loads, estimating the aggregated power demand without any centralized server and creating a virtual "community" of smart buildings in the small island. The main advantage of this control scheme is that it provides a better quality of experience to the users and offers additional flexibility for the energy producers to accommodate loads throughout the day.

Within this context, energy management systems are required to manage the entire microgrid, scheduling the loads and storage in response to: (i) the current and predicted generation levels; (ii) the current and future electricity prices; (iii) the user preferences and consumption patterns; and (iv) the limitations of the electric circuits. However, ultimately, flexibility will result from the willingness of the consumers to adapt their consumption pattern according to electricity generation and through the electrical interconnection with the Portuguese mainland grid, which can potentially absorb the electricity in hours of excessive production, providing electricity in hours where there is less local production.

This study has also shown that the electricity demand on Culatra is strongly impacted by residential consumption. Thus, in the residential sector, energy savings through retrofitting can avoid peaks in demand and reduce consumption. The retrofitting of the building mass is, in general, required to become zero-energy housing and to have the least impact on the natural park, also having a large effect on the overall demand on the island. The recommendation that arises from the PV installation proposed at Culatra shows that a broader range of solutions are required which may result from a combination of: (1) complementary RES, like small wind turbines, whenever generation periods are unpaired with the solar radiation, (2) battery units that allow storing energy for later usage, and (3) DR measures that adapt the consumption curve to the generation curve. The fact that the Culatra Village is part of a Natural Park limits the resources that can be used for energy generation and, therefore, the installation of wind turbines is not an option. The environmental constrains also limit the occupancy of new areas for solar generation, as such the increment of solar generation must be achieved by installing PV systems on the existing housing, which is dependant from the housing' legalisation process. The photovoltaic project considered here requires an area of nearly 1700 m^2 of solar modules. However, and as shown in Table 6, replacing the old asbestos fibber cement roofs with new roofs fitted with PV generation would potentially increase the generation to over 4 times the initial project (i.e. which only considers public infrastructure).

6. Conclusions

Given the critical importance of local public support for green energy infrastructures, social scientists have developed a multitude of conceptual frameworks explaining public attitudes regarding energy transitions. The 'Culatra2030 - Sustainable Energy Community' initiative is a demonstration project on the island of Culatra in Algarve, Portugal, covering multiple aspects of green transition. Rather than the development of new technology, the key perspectives are the holistic model and the demonstration character of the initiative. The central ambition is to transform all structures on the island to become energy self-sufficient. Considering the environmental constrains and socioeconomic settings of a fishing community, a QH model was applied through the means of a three phase Community Participatory Diagnosis, which brought together public entities, academia, companies and communities. Following the initial stage, a new governance system for participatory exploration of transition pathways was put in place.

The novelty of this study is associated with the global methodology used, i.e., combining a Community Participatory Diagnosis with a technical analysis of the requirements and economic benefits of installing renewable based energy sources. The community was involved since the beginning of the process, which has been shown to be key to support the transition from national level to local level investments. This allows the selection of which technological solutions to install, increases the awareness and involvement of the economic costs and benefits of the associated investments, potentiates a community-based management of the system to be installed and includes the required DR measures, among others. The involvement of the stakeholders in this process, especially those with legal jurisdiction in the area, was also important in the context of the island, constrained by the fact that it belongs to a natural protected park.

This participatory model proved to be of considerable help in streamlining decision-making processes and ensuring feasibility of all projects from the outset. The new participative approach compares favourably to the past situation, where a multiplicity of bodies in the small territory were acting in an unconnected and uncoordinated way. The methodology applied here also emphasized the importance of the social component associated with the constitution of future energy communities, participated in and represented by the agents in the community. It also allowed categorising different pillars of energy transition.

While the implementation of the full range of solutions for Culatra' CETA is still underway, several remarkable achievements are already visible. Based on the existent energy system and consumption profile, a PV power plant was designed for the public infrastructure. Its preliminary design was based on 859 standard monocrystalline PV modules with a peak power of 360 Wp, optimizing surface use and electricity generation output.

The results show how using only publicly available infrastructure, PV production can reduce the dependency from the grid by one third. Complementary, on average, 85.7% of the energy produced in the island can be auto consumed; whereas the remaining 14.4% of the energy produced can be injected in the grid. There is a huge potential to increment PV production using existent residential infrastructure to achieve a total capacity of nearly 2500 kWp, generating significantly more energy than the one that is consumed at present, which can be injected in the grid, and/or stored and diverted for other uses by applying DR on a context of energy community sharing. Nevertheless, the results also show that installing more solar generation infrastructure, if not complemented with other storage solutions or DR measures, will not bring a proportional economic benefit.

The most important lessons learnt from Culatra2030's experience, so far, are that: (1) it is essential to include the community's perspective in order to truly understand actual needs; (2) broad citizen participation and strong cooperation between citizens, authorities, researchers and companies provide the most realistic basis for green transformation - the comprehensive and thorough CPD carried out has been a key ingredient of success; (3) a wide combination of all potential technology pathways, whether they concern batteries, electric vehicles, retrofitting of homes, or heat pumps, etc., need to be carefully aligned to achieve a reliable, community-owned, decarbonised energy system; and (4) the benefits of ownership in infrastructure projects, such as RES production, are claimed to include increased responsiveness to the needs of a community and the community valuing the projects more highly and committing easily. This does not only constitute the key element for institutionalising the islands' energy community, but as well, and not less, to assume and negotiate the implementation of wider complementary and supplementary actions towards the autonomy and the global sustainability of the island.

Finally, the success of Culatra 2030 still depends on new regulatory developments and incentives for the creation of energy communities yet to be put in place. Further adaptation of urban administrative procedures on the island and better availability of funding sources are also needed for test beds to ensure optimum adaptation of new technologies to community's specific needs.

CRediT authorship contribution statement

A. Pacheco: Funding acquisition, of data was secured by, Formal analysis, and interpretation of data by all authors, Writing – original draft, the article, The final version was submitted by, which was also responsible for organizing the reply to the reviewers and revise the final version to be submitted. **J. Monteiro:** Funding acquisition, of data was secured by, Formal analysis, and interpretation of data by all authors, which was revised critically by, for important intellectual content, Writing – original draft, the article. **J. Santos:** Formal analysis, and interpretation of data by all authors, which was revised critically by, for important intellectual content, Writing – original draft, the article. **C. Sequeira:** Formal analysis, and interpretation of data by all authors, which was revised critically by, for important intellectual content, Writing – original draft, the article. **J. Nunes:** Formal analysis, and interpretation of data by all authors, Writing – original draft, the article, which was revised critically by, for important intellectual content, All authors made substantial contributions to the conception and design of the study.

Declaration of competing interest

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

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Acronyms

CE4EU	Clean Energy for EU Islands Programme
CETA	Clean Energy Transition Agenda
CPD	Community Participatory Diagnosis
CAPEX	Capital Expenditure Costs
DR	Demand Response
DSO	Distribution System Operator
IRR –	Internal Rate of Return (%)
LTYA	Long Term Yield Assessment
NPV	Net Present Value
OPEX	Operational Expenditure Costs
PR	Performance Ratio (%)
PV	Photovoltaic
QH	Quadruple Helix
RES	Renewable Energy Sources
SCR	Self Consumption Ratio (%)
SSR	Self Sufficient Ratio (%)
V2G	Vehicle-to-grid

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