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Towards climate adaptation: a case study of a Coastal City in Portugal

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ABSTRACT

The present study focuses on the use of complementary numerical tools to support the development of a climate neutrality roadmap for Cascais, a coastal Portuguese city and one of the nine pilot cities in the *Re*-Value project. The results contribute to refining the roadmap and updating Cascais' long-term Territorial Transformation Plans to accelerate its journey to climate neutrality by 2050. For this, a spatial analysis was conducted to assess the potential for rooftop solar PV, onshore wind energy, and wave energy along the coastline. Additionally, an innovative and simplified Decision Support Tool (DST) was developed to support municipalities in the development of their climate neutrality roadmaps and was used in the design of the scenarios and trajectories, which are now being integrated into the climate neutrality roadmap for Cascais. The DST tool results show that in the High Development scenario, when compared with the reference year of 2019, the total final energy demand can decrease by 7.2 % in 2050 due to the implementation of energy efficiency measures following the concept "Energy Efficiency First" and along with the increase of electrification, the introduction of hydrogen in the transport sector, and a broader implementation of renewable energy in the urban fabric and public spaces, Green House Gas (GHG) emissions can decrease by 82 % in 2050.

1. Introduction

1.1. Context

In the last years the Member States of the European Commission (EC) have been making an effort to meet the goals established in the National Energy and Climate Plans in what concerns Energy and Climate. In this scope, the EC addressed the importance of the climate-neutral and smart cities through the funding program EU Missions, as a response to these topics, especially in what concerns the urban and energy challenges to promote innovative solutions and strategies and to deliver tangible results in the horizon 2030–2050. Following these challenges the EU funded several projects in the Smart-Cities' area that present different approaches and contributions to meet the Energy and Climate goals of the different Member States, and also several initiatives have arisen in cities all over the world establishing strategies and policy recommendations guidelines for the development of these cities [1]. The European Union (EU) fully recognizes the significance of sustainable development and aims to reduce its carbon footprint and make Europe a global role model in energy transition. In 2019, all EU Member States encoded this ambition into their National Energy and Climate Plans 2030 [2]. The EU Council has set targets on greenhouse gas reduction, renewable energy production and energy efficiency for 2020 and 2030, which paves the way to the long-term goal of a climate neutral economy by 2050 [3]. According to the governance of the energy union and climate action rules entered into force in December 2018, EU countries are required to develop integrated National Energy and Climate Plans (NECPs) that will cover the five dimensions of the energy union i.e. (i) security, solidarity and trust, (ii) a fully integrated internal energy market, (iii) energy efficiency, (iv) climate actions – decarbonizing the economy and (v) research, innovation and competitiveness for the period 2021 to 2030. For Europe to be climate neutral by 2050, EC proposed several approaches to stimulate energy transition and climate neutrality in urban environment, addressing different scales from city level to districts and neighborhoods. For example, the European Innovation Partnership on Smart Cities and Communities (EIPSCC) established the initiative on Positive Energy Blocks (PEBs) in 2016 [4] supported by EC pilot projects towards Positive Energy Blocks/Districts as a core topic of the Horizon2020 Smart Cities and Communities call LC-SC3-SCC-1, with an aim to drive the deployment of PEBs in Europe. Moreover, the Strategic

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Energy Technology Plan (SET Plan) of the EC aims to accelerate the development and deployment of the most impactful technologies in the EU's transformation into a low-carbon energy system by coordinating research and innovation efforts amongst EU countries, companies, research institutions, and the EU itself. In June 2018, the SET Plan on Action 3.2 "Smart Cities and Communities" was endorsed by the EC [5]. The main objective is to develop integrated and innovative solutions for the planning, deployment, and replication of Positive Energy Districts (PEDs). Several aspects related to PEDs and the energy transition at district scale were addressed from definition perspective [6,7] and implementation methodology [8] and [9]. Within the context of the initiative EU Missions launched in 2021 by EC [10] the mission on Climate Neutral and Smart Cities will help meet the goals and targets set out by international policy frameworks such as the COP21 Paris Agreement, the UN's Sustainable Development Goals (SDG11), the Urban Agenda for the EU and the Habitat III New Urban Agenda, as cities play a key role in all of them. The main goal is to reach 100 climate-neutral cities by 2030, promote and showcase 100 European cities in their systemic transformation towards climate neutrality by 2030. To support these ambitious targets the research and innovation funding programme, Horizon Europe (HE) launched several calls, one of which is the Research and Innovation actions to support the implementation of the Climate-Neutral and Smart Cities Mission (HORIZON-MISS-2021-CIT-02). In this context, the authors of this study intend to share the firsts results from a research project funded by HE within the referred call, Climate-Neutral and Smart Cities Mission, focusing on the urban planning and design for sustainable, resilient and climate-neutral cities by 2030.

1.2. Numerical tools for the urban development and strategic plans implementation

Integrating complementary numerical tools can significantly enhance the development of urban planning and roadmaps. For instance, Geographic Information Systems (GIS) enable planners to analyze spatial data, assess land use patterns, and visualize infrastructure layouts. When combined with scenario modeling tools like ArcGIS Urban, planners can simulate various development scenarios, evaluating the impacts of different zoning regulations or infrastructure investments. This synergy allows for data-driven decision-making, facilitating the creation of sustainable and resilient urban environments. By leveraging the strengths of each tool, cities can develop comprehensive plans that address current challenges and anticipate future needs.

Urban planning in today's complex cities demands the use of advanced tools to gather the data available, define diagnostics and analyse trends and scenarios in scope of supporting the decisions that foster sustainable, climate neutral environments and energy transition. However, practitioners and municipal technicians need faster and more user-friendly tools to efficiently carry out their activities, take decisions and develop urban plans. In the context of urban planning the use of simple complementary tools can often be more practical than complex numerical models, especially for preliminary assessments and communication with stakeholders.

The cities plans and roadmap development is developed in phases, as for example data collection, diagnostic and base line setting, developing scenarios, mitigation measures assessment and mapping of the results.

For example, one of the main solutions supporting the development of urban analysis in cities is the use of planning tools for the development of Renewable Energy Systems (RES). These tools are crucial for integrating renewable energy sources into urban infrastructure, enhancing energy efficiency, and reducing carbon footprints. They enable cities to assess local renewable energy potential, optimize energy distribution, and implement sustainable urban energy systems. By leveraging these planning tools, cities can create comprehensive strategies for renewable energy integration, aligning with global goals for a carbon-constrained future. In the last years the growing concern with the cities' sustainability led to the development of different methodologies and tools to the evaluation of RES implementation in the cities' context and to an efficient management of the energy demand and supply towards more energy efficiency at the municipality scale. The existing tools can cover different scales inside a city, from groups of buildings or neighbourhoods to the whole city or municipality area. Examples are Urban Building Energy Modelling (UBEM). These models can be applied to larger scales such as neighbourhoods or cities instead of only building small blocks. Also, they can be divided according to the scale and modelling approach - physics-based dynamic, reduced-order and data-driven, [11].

The integration of renewable energy systems (RES) in cities also faces several challenges related with the different technologies and their locations. In this sense, a suitable and effective resource assessment needs to be performed for each technology, and/or a combination of technologies considering hybrid systems installation. For this end, the most common methods rely on the use of microscale models that can estimate the energy production – WASP [12], WindSim [13], and others, for wind applications, and SolarGIS [14], PVGIS [15], PVsyst [16] for Photovoltaic systems. The outputs of these models, together with a demand assessment in the same locations, constitutes relevant input for Energy Modelling in urban environments. Examples of Energy Models widely applied and considering a large number of factors (socio-economic aspects, energy production and demand, application to different scenarios, policy making); are, Open Source Energy Modeling System (OSeMOSYS), MARKet Allocation (MARKAL), Integrated MARKAL-Energy Flow Optimization Modeling System (TIMES), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), Modular Energy System Analysis and Planning Environment (MESAP), EnergyPLAN, Long-range Energy Alternatives Planning System (LEAP) and Renewable Energy Scenario Generation (RESGEN) [17].

The study and consideration of different scenarios in a given region or city, is of utmost importance and enables the development of tailored and effective Energy Plans, enabling to identify the most interesting solutions for the energy system decarbonization and the fulfilment of the Energy and Climate goals.

The cities renewable potential assessment, conditions/restrictions application and electricity demand, involve large amounts of information. For this end, the use of GIS is valuable due to its capabilities to handle different types of information (maps, tables) and develop automatized procedures to achieve the objectives [18,19].

Finally, an Energy Plan for a certain city or region, is only effective and successful if it has into consideration the socio-economic context of the area of interest. For this purpose, the public consultation, sectoral analysis and scenario consideration is required. Questionnaires to the inhabitants and stakeholders have become very popular for this characterization, as well as the organization of workshops that, on one hand, present the project/plan to the participants, and on the other hand, enable to collect, face-to-face feedback from the relevant actors [20,21].

1.3. Re-value project

The main goal of *Re*-Value project is to test, capture and share how to create value through urban quality in a holistic approach towards climate neutrality. The project started in 2023 and will develop the research activities for a period of 4 years. 9 cities take part of this project, 4 of them represent the Leading Cities (Aalesund, Bruges, Burgas, Rimini) and they will demonstrate, full-scale, how integrated urban planning and design can be optimally developed to achieve climate neutrality and significantly reduce GHG emissions by 2030. The other 5 cities represent Replication (or following) Cities (Cascais, Constanta, Izmir, Pisek and Rijeka), and will learn, replicate and develop their own participatory story-building, data-driven scenarios and financial and partnership models on integrated urban planning and design to accelerate the path towards climate neutrality. In addition, these Cities will deliver Detailed Roadmaps for their Waterfront Pilots and update their long-term Territorial Transformation Plans aiming to reach climate neutrality by latest 2050. The project is structured to facilitate the exchange of experiences between leading and follower cities through a dedicated “Community of Practice” work package. This will ensure effective knowledge sharing, mutual learning, and the alignment of Roadmaps and long-term Territorial Transformation Plans with the *Re*-Value Impact Model and the objectives of the EU Cities Mission. The main objectives of the project consist of (i) proposing, developing and testing a multi-modal impact model for value-based urban design and planning in the 9 participating cities, (ii) implementing *Re*-Value solutions and actions in the 4 Leading cities, replicating actions in the 5 Replication cities, together with (iii) roadmaps for implementation and replication respectively, (iv) monitoring activities, (v) implementing and consolidating a community of practice between the partners and stakeholders, and (vi) disseminating the results of the project. The methodology of the project is driven by 6 Systemic Challenges (SC) along wit0h 3 Innovation Cycles (IC) as is illustrated in Fig. 1. The 6 SC, namely SC1 - Changes in governance, regulatory structures, advocacy, SC2 - Cultural and spatial quality, SC3 - Data-driven co-creation and Digital Twins, SC4 - Financial and circular value chains, SC5 - Energy and mobility and SC6 - Nature-based solutions, will help the 9 cities to implement and replicate a portfolio of solutions. Building with the support of a Community of Practice, *Re*-Value follows an approach to capture the added value and co-benefits to the stakeholders through an Impact Model, to be then used as basis for the Innovation Cycles, namely: (i) IC1 - The story-building cycle to foster ownership by the community and to ensure implementation of the measures, (ii) IC2 - The scenario-building cycle to establish data-driven strategies to support urban planning and design, and (iii) IC3 - The investment and partnership building cycle to feed into the detailed roadmap of the Waterfront Pilot.

1.4. Objectives of the study and structure

This paper presents the initial work developed in the scope of *Re*-Value project, focusing on the replication city Cascais, located on the coast of Portugal. One of the main outcomes of the project in Cascais city is the development of a Detailed Roadmap and a long-term Territorial Transformation Plans aligned with the *Re*-Value Impact Model and the EU Cities Mission based on feasibility studies with co-benefits and of

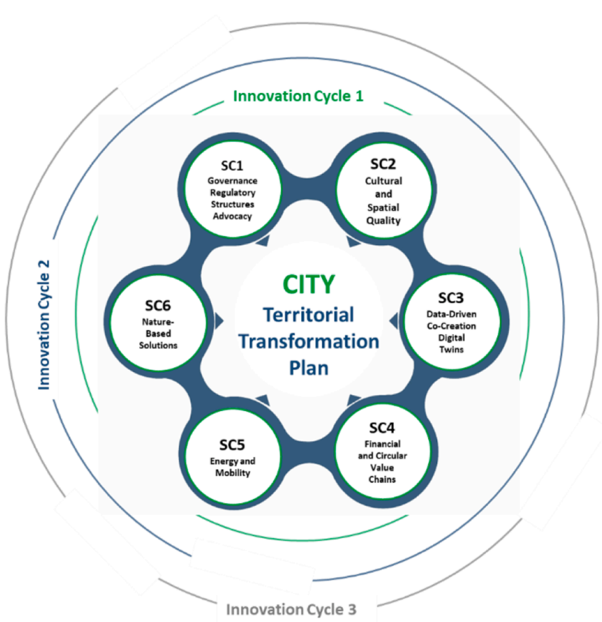

Fig. 1. *Re*-Value approach.

climate neutrality and urban quality, viable investment and partnership models, a strong and widely supported story, and a well-established support base for co-creation with local citizens and professional stakeholders.

In order to support the development of the Cascais detailed Roadmap implementation, numerical tools have been used, focusing in two main aspects: (i) the characterization of the Renewable Energy (RE) potential (solar, wind and waves) using a spatial analysis and (ii) analysis of the evolution scenarios related with Energy Demand and corresponding GHG emissions in several sectors (residential, commercial and services buildings, industry and transport).

This research presents a development planning tool, that enables to draw scenarios based on the information from different sectors, produced in a way that enables the use by someone that doesn’t have modeling skills. It is easily updated which reflects the reality of the cities and can be applied to different geographies due to the way it was programmed. Also, the paper includes the renewable resources maps, that take in consideration the urban fabric, which is important for the accuracy of the results, even, when the objective is planning and not a specific project in a specific location/building. This asset contributes to better tailor mitigation measures having into account the resource that is most suitable for a certain area inside the municipality.

The study is structured in 4 main sections starting with the introduction, the methodology for the roadmap development is presented in Section 2, followed by the preliminary results for the Cascais city roadmap presented in Section 3. The study ending with the conclusions in Section 4.

2. Methodology for the development of Cascais’ roadmap on climate adaptation

The rationale of the *Re*-Value project is to demonstrate how climate neutrality and urban quality can be aligned, by re-valuing their connection to the waterfront, strengthening co-benefits and mitigating potential adverse impacts - in summary, making their urban transition irresistible for citizens and professional stakeholders. The ultimate goal in the context of this project is the development of a long- term Territorial Transformation Plan (TTP) and to develop participatory story-building, data-driven scenarios and financial and partnership models on integrated urban planning and design to accelerate its journey to climate neutrality. Although the city of Cascais has climate mitigation actions planned under the 2050 Carbon Neutrality Municipal Roadmap and Cascais Sustainable Energy Strategy, the project and the *Re*-Value roadmap for Cascais will therefore contribute to redesigning Cascais’ ambition for carbon neutrality to make it more integrated, cooperative, and active, allowing to transcend traditional accounting and helping to invest with more value and lower risk, especially in the coastal zones.

Firstly, an analysis and identification of the coastal pilot zones has been made, and these pilot coastal zones are described in the following sub-section.

2.1. Cascais waterfront replication city description of the pilots

The city of Cascais, currently with around 219 0636 inhabitants, is composed of different urban centres along the coast characterised by a continuous urban line. The city has a comprehensive sustainability and climate action policy, confirmed, among others, by its PAES Cascais 2030, Local Sustainable Energy Plan and Expression of Interest for the Cities Mission and Municipal roadmap for carbon neutrality by 2050. In its waterfront pilot project, Cascais intends to test participatory interventions for nature-based solutions on natural and urban spaces to improve resilience and biodiversity and increase accessibility through the development of cycling lanes, pedestrian walks and active mobility. In the energy sector, the city intends to boost the production of renewable energy as well as promote the development of local energy communities in vulnerable areas, in cooperation with local residents’ associations, schools, art and culture organizations, beach concessions, surf schools and associations, user groups (sport) and environmental associations. In its 2019 Roadmap for carbon neutrality, Cascais had already identified that electrification should contribute significantly to its decarbonization. Electricity produced from renewable energy sources (RES) has low GHG emissions and therefore contributes to this goal in the three sectors that will be studied, namely in buildings, industry and mostly in the transportation sector. For that purpose, the development and installation of RES is encouraged. The city will start by focusing on photovoltaic systems, namely on rooftops and Building Integrated Photovoltaics (BIPV), because it is easier and faster to install, but will also investigate the urban integration of small wind turbines and harnessing wave energy along the coast. In this project, Cascais has proposed three pilots along the coast of the municipality – Carcavelos Beach, Guia coast and Ribeira das Vinhas stream. Fig. 2 shows the location of the three pilots.

Pilot 1 - Carcavelos beach (Fig. 3) is one of the most popular beaches of the outskirts of Lisbon, Carcavelos is extensively used during the whole year (incl. surf destination) with higher demand in the summer period (over 20 000 daily users). **Pilot 2 - Guia Coast** (Fig. 4) starts close to Cascais city centre and extends for approximately 3 km of seaside cliffs. This coast is followed by a road and an extensive cycling and walking lane with a high demand during the whole year. Along this coastline there are numerous cultural and natural attractions such as “Boca do Inferno” rock formation and “Casa da Guia” museum and commercial set, where there is a strong presence of high demand restaurants and terraces. The green corridor of **Pilot 3 - Ribeira das Vinhas** (Fig. 5) was subjected to naturalization in over 8 km around the stream in order to reduce flood risk and heat island effect, while providing a valuable trail for recreation and sustainable commuting for over 35 000 citizens. Ribeira das Vinhas cycle lane provides therefore an easy access to the city centre promoting active mobility from densely populated zones while contributing to climate resilience.

2.2. *Roadmap first phase development*

The objective of the roadmap in this first stage was to describe the 3 pilots, collect georeferenced data and other relevant data, compile the plans and laws that apply to them and relate that information with the 6 systemic challenges that are to be tackled in this project. The 2 systemic challenges firstly analysed were SC3 - Data Driven Co-Creation and Digital Twins and SC5 - Energy and Mobility, which led to two main steps of the development: (i) the characterization of the renewable energy potential based on local resources in the city of Cascais and (ii) the preliminary simulation of evolution scenarios for energy demand and GHG emissions in some sectors. The information used in the development of the roadmap for the city of Cascais is based on the Municipality georeferenced database, and on public information related with the different themes (layers) relevant for the establishment of the long-term Territorial Transformation Plan to be implemented towards climate neutrality in this region. All the information is processed and introduced in a Geographical Information System, where the adequate procedures are implemented (e.g. georeferencing, map algebra, SQL conditions, among others).

Fig. 2. Cascais’s pilots’ location.

Fig. 3. Pilot 1 - Carcavelos beach.

Fig. 4. Pilot 2 - guia coast.

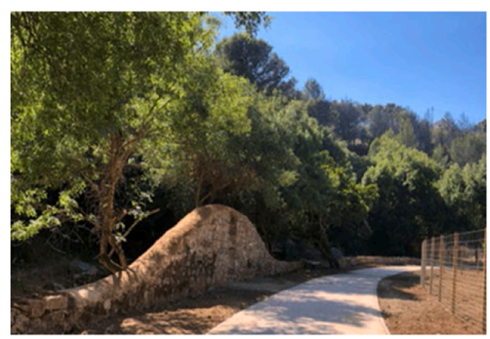

Fig. 5. Pilot 3 - ribeira das vinhas stream.

2.2.1. *Characterization of the renewable energy potential – spatial analysis*

Aiming to increase the use of renewable energy in Cascais Municipality to meet the carbon neutrality objectives in 2050, an assessment of the renewable potential was performed in order to understand the contribution that the different renewable sources could give to the energy goals of the city, through the use of small wind turbines [22], wave energy converters [23], and solar technologies and materials [24,25]. Therefore, the wind and solar resource assessment was mapped for the whole city, and for the wave energy just in Cascais coastline. The characterization of the available renewable resource was performed through the use of three different approaches, according to the renewable source.

Wind resource assessment. The methodology used in creating the wind energy potential map is based on the generation of a digital terrain model which includes the terrain and the existing buildings, thus representing an urban digital terrain model: U-DTM. The urban DTM was developed in a way that represents from one side the orography of the terrain in the municipality region, and from another the urban fabric. The method used to develop the U-DTM is based on geographical information techniques that include resample and map algebra operations. The geometry of the buildings (polygons representing the urban fabric) and corresponding buildings' heights is entered into a geographic information system to make the necessary operations to allocate the heights to the polygons representing the buildings in an accurate way (if they are not already associated). These are then subjected to a rasterization process in order to transform the surface into a grid of points. This grid of points is then added to the terrain orography (operation "sum"), also in raster format and with the same pixel size, originating a digital terrain model. Fig. 6, illustrates the process and the obtained U-DTM for Cascais municipality.

In the case of wind potential assessment, this U-DTM represents a very complex terrain and be used as input for a standard wind resource assessment model (e.g. Wasp) with the necessary adaptations to the model to be used in the wind resource assessment, and, with a very good representation for planning purposes. In addition, this methodology strongly reduces the computational costs associated with standard CFD (Computational Fluid Dynamic) models to simulate groups of buildings; it simplifies the geometry of the urban mesh and allows to extend the area of simulation to a city scale. The obtained results are then validated with experimental data obtained in two locations of the Cascais municipality – Lidar sensor installed on the rooftop of Pedra do Sal's environmental interpretation Building in Estoril (data used is referred to the period from June 2012 to May 2013 with inter-annual correction of the horizontal mean wind speed values) and one anemometric station installed at Tires' aerodrome, in São Domingos de Rana (measurements made between 2009 and 2012 of measurements). More details on the procedures and results can be consulted in Simoes et al. [26].

Solar resource assessment. The average yearly Global Horizontal Irradiation (GHI) at ground level and in rooftops was assessed for Cascais municipality considering the terrain's slope and the buildings' shape and height by also using a U-DTM, equivalent to the one described for the wind speed assessment, and solar analysis tools in GIS software. In this case, the U-DTM, corresponds to the one used in the wind potential assessment. The main difference from the wind potential assessment case, is that there is no need to adapt the U-DTM to the format of any other models, since the solar radiation mapping is performed with the same GIS. In this case, the configuration of the urban fabric remains unchanged when compared with the real buildings, with exception of the rooftops that are usually not easily available in 3D The GIS solar radiation analysis tools calculate insolation across a landscape, based on methods from the hemispherical viewshed algorithm developed by Rich et al. [27] and further developed by Fu and Rich [28]. The total amount of irradiation calculated for a particular location or area is given as global irradiation. The calculation of direct, diffuse, and global irradiation is repeated for every location on the topographic surface, producing irradiation maps for an entire geographic area. It is important to note, that the results obtained in the spatial distribution of the solar radiation, where validated for different locations in previous projects and in the case of Cascais Municipality, in some areas, were compared with satellite data from the European platform PVGIS [29].

Wave energy. The energy contained in a sea state can be described from its directional spectrum of frequency and wave propagation direction, Mendes et al. [30]. The spectra used here was obtained for a Mar3G (Ondatlas) sea wave model [31], applied in this case to four locations (Cabo Raso, Guia, Cascais, Parede) in the municipality of Cascais, that are shown in Section 3.1, Fig. 11.

Based on a set of spectra representative of the waves at these four points, it was possible to determine the power density of the waves and their average direction for each of these points (and for each wave spectrum observed at the site) considering the Mendes et al. [30] approach. Scatter plots of the power density as a function of the average power direction were determined, which led to the bivariate probability distribution. The bivariate tables were divided into 30º sectors with the commonly used denomination (e.g. North-North-North-East, N—NNE), and power classes that are not equally spaced, their interval increasing with the value of the power density, as will be seen in the radial graphs of Section 3.1. Corresponding to the direction from West to East, Cabo Raso is the most Western location and Parede is the most Eastern one.

2.2.2. *Decision support tool for supporting climate neutrality roadmap*

Another step in the construction of the local roadmap towards climate neutrality is the assessment of a mitigation solution portfolio, based on different development scenarios. For this analysis, a simplified simulation tool [32] being developed at LNEG was used. This decision support tool, (DST) aids municipalities in designing their decarbonisation roadmaps and has 3 main components, as illustrated in Fig. 7. Each of the 3 simulators has specific objectives and roles as follows:

(i) Scenarios' simulator that enables to design in an interactive way socio-economic scenarios for different sector' variables that inform local decarbonisation trends, developed using Excel ©.
(ii) Mitigation simulator, that enables to translate those scenarios in GHG emissions, considering the identification and prioritisation of mitigation options (technological and behavioral changes) tailored to the Portuguese municipalities' reality, being developed using Excel ©.
(iii) Mapping simulator that enables the mapping of the "hot spots" of GHG emissions at a local scale, being developed using ArcGIS ©.

The three simulation components of the decision support tool are linked to each other, being sequential and complementary. The scenarization tool builds on the specific local socioeconomic variables along with the other activity variables relevant to local decarbonization, providing the expected outcome of local GHG pathways based on the evolution for distinct scenarios. The mitigation component assesses the impact of different combinations of mitigation options and calculates the differences of the GHG emissions evolution under mitigation trajectories compared with the business-as-usual ones. Finally, the GHG

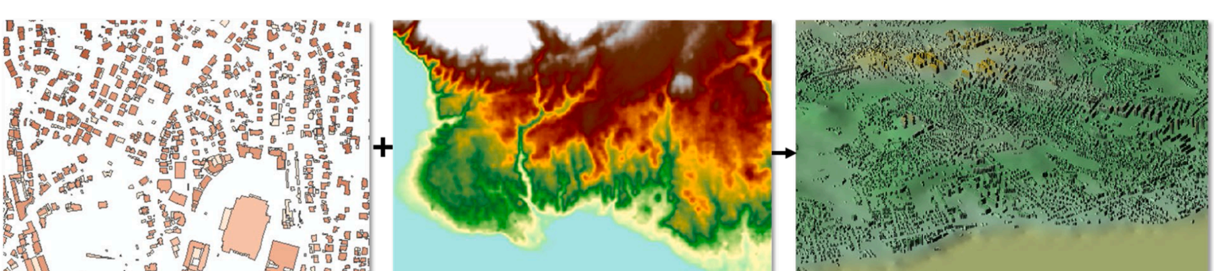

Fig. 6. Schematic representation of the development of the U-DTM.

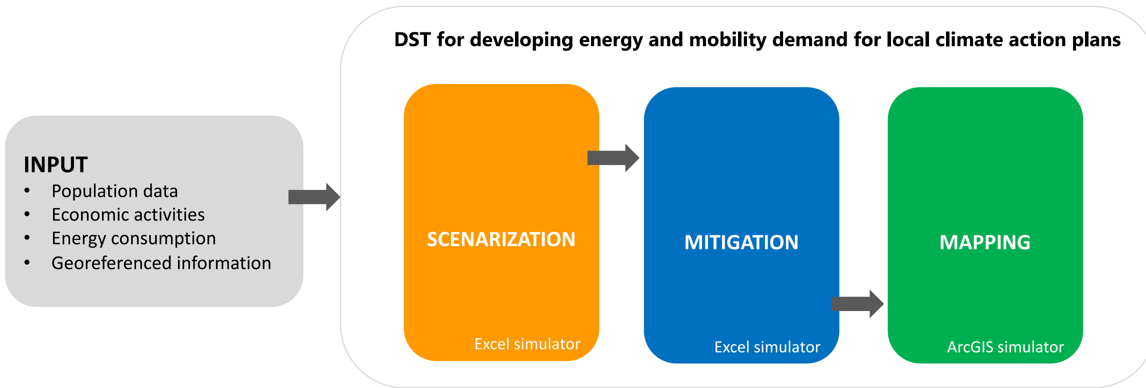

Fig. 7. Decision-support tool for developing energy and mobility demand for local climate action plans.

emissions mapping tool illustrates the future scenarios considering specific city parishes, depicting the final outputs of GHG emissions reduction trajectories resulting from the mitigation simulator, for 2030, 2040 and 2050, and for each parish.

The DST benefits from the use of official and publicly available data sources as well as a straight collaboration and co-development process with specific local stakeholders, for each of the simulator components, which also included local administrative data sources, which enabled the more detailed socioeconomic and spatial characterisation of case study areas within the city.

The tool is under development and the first simulator related with the scenarios' design is operational and has been used in this study. The architecture behind the scenarios' simulator is illustrated in Fig. 7. This simulator enables the drawing of evolution trends and scenarios representing socio-economic and other variables' evolution and will allow to test the impact of different pre-established assumptions for the evolution of those variables in several areas from Gross Domestic Product (GDP) and population growth to energy demand, and consequently the respective GHG emissions.

The main variables considered in this study were GDP, population, number of inhabited households, and energy demand in residential, commercial and services buildings, industry, transport and GHG emissions in these last four sectors. The general methodology for the establishment of the development scenarios is described in Fig. 8.

The first step is the selection of a reference year, that will be used as baseline scenario for the whole study, and the characterization of the current situation in terms of energy demand and equivalent CO_2 emissions. The second step is the simulation of the future scenarios that will depart from the baseline characterization data, using other inputs related with the city itself, such as population data, economic activities evolution and geographical data.

The simulation scenarios are then designed according to the main energy consuming sectors, namely for buildings – residential and commerce & services, industry and transports, and the energy demand evolution along with their GHG emissions is obtained for each one of them. The mitigation simulator uses the same framework and

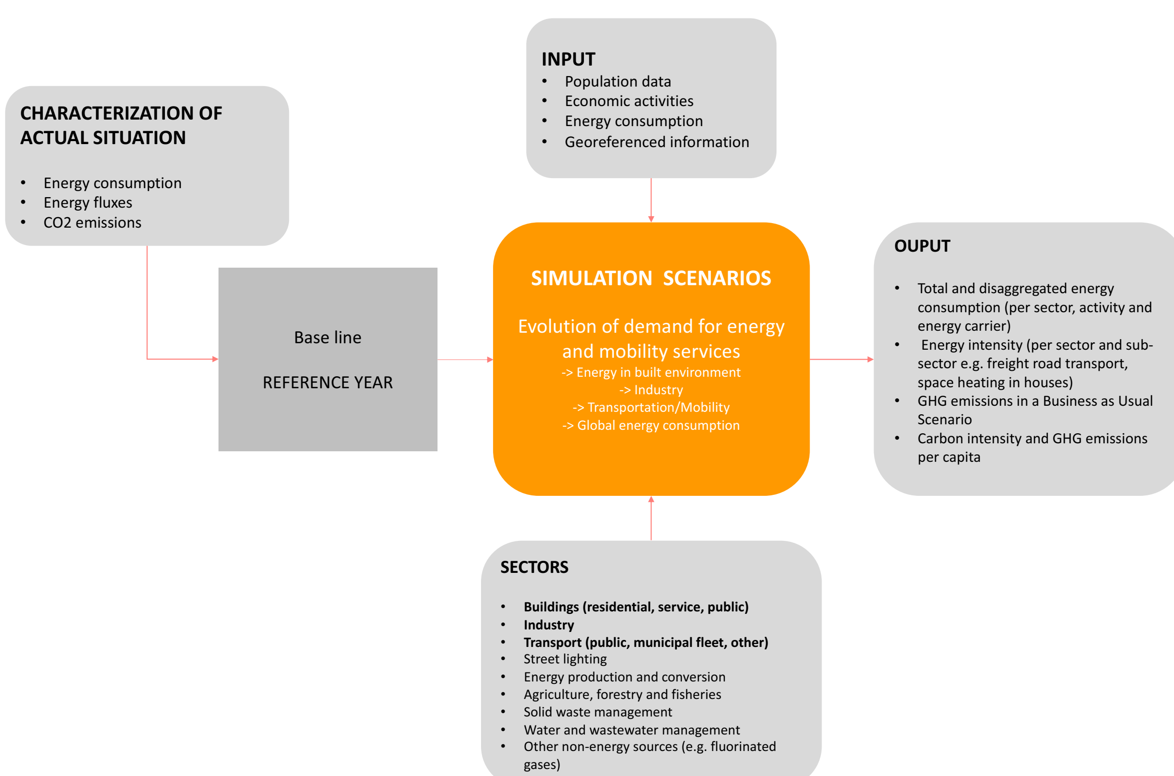

Fig. 8. Scenarios' simulator.

additionally embeds a set of GHG mitigation measures, which best fit the specificities of the city, related to technological, environmental and socio-economic impacts. These mitigation measures are chosen and their cumulative impact quantified against the respective business-as-usual GHG emissions evolution, in each previously defined scenario.

Finally, the estimated GHG emissions will then be mapped using the geospatial data tool.

2.2.3. Data sources

The main sources of information for the development of the DST tools and characterization of the historical and reference energy demand of Cascais municipality, allowing an in-depth knowledge of the municipality and its expected future evolution, have been institutional sources, such as the sectorial energy and primary energy sources demand from the General Directorate of Energy and Geology (DGEG), statistics from the National Statistics Institute (INE) on population and buildings included in the national population CENSUS of 2011 and 2021, on mobility included in the Lisbon Metropolitan Area (AML) Sustainable Urban Mobility Action Plan, Buildings Energy Certificates have been provided by the Energy Agency (ADENE), and GHG emissions data was collected from the Portuguese Environment Agency (APA) yearly reports and database. Other relevant data sources for the development of the scenarios were also the municipality's experts' information and administrative data gathered (eg. Energy demand in municipal buildings and public lighting), the previous Cascais Decarbonization Roadmap (prepared in 2019 with 2015 data) and the Cascais Climate Plan focused on mitigation measures. Besides the compilation of data to define the trends for this specific municipality, the scenarios were also built in agreement with the assumptions and goals defined in the National Energy and Climate Plan for 2050 (NECP 2050).

2.2.4. Description of the scenario tool

The scenario tool will facilitate the development of scenarios related to socio-economic evolution and other activity variables, enabling consulted stakeholders to interactively test the impact of various assumptions on the progression of these driving factors, which in turn have consequential effects on energy demand and GHG emissions. The key socio-economic variables considered are the Gross Domestic Product (GDP), the population evolution and the inhabited residential buildings.

2.3. Considered scenarios

A reference scenario aims to reflect an "average" year representative of the current situation of the municipality and is denominated as "Business as Usual" (BAU). The two other scenarios are the "High Development" scenario were the increase of population, investment and usage of innovative technologies is considered, and "Recession" scenario where there is a decrease in population, in investment and the continued use of outdated technologies. Each scenario is associated with a narrative of the city driven by the assumptions shown in Table 1.

Regarding transport, the passenger-kilometre (pkm) quantity shown in Table 1 is defined as the product of occupancy, vehicle stock and distance travelled.

It is important to note that this type of tool requires periodic update that can lead to minor adjustments according to the evolution of the different actors in the sectors included in the scenarios and according to the monitored variables. This is especially important because of the strong dependance on the political and socio-economic environment that can change in a short number of years.

Table 1
Assumptions for each scenario.

High Development Scenario	Business as Usual Scenario	Recession Scenario
High population growth until 2050 Nr. of inhabited buildings grows significantly in all parishes	Moderate population growth until 2050 Nr. of inhabited buildings grows moderately in all parishes	Population diminishes in all parishes Nr. of inhabited buildings follows population trend
Services and tourism evolve 25 % more of what is foreseen in the RMNC 2050 for 2030 and 50 % more for 2050	Services and tourism evolve as foreseen in the RMNC 2050 in agreement with the growth rates defined in the NECP	Services and tourism are 75 % of what is foreseen in the RMNC 2050 for 2030 and for 2050 follows 50 % of the GDP growth as defined in the NECP
pkm according to population evolution	pkm according to population evolution	pkm according to population evolution

3. Preliminary results for Cascais roadmap phase 1 results

3.1. Characterization of the renewable potential in Cascais city – spatial analysis of the renewable resource

Taking into account the methodology used for the characterization of the RE sources that was described in Section 2, the following 3 maps were produced. Map 1shows the average wind speed at a height of 10 m above the buildings for Cascais municipality (Fig. 9), were the highest wind speed obtained is 8 m/s and the lowest 3.6 m/s.

This lowest velocity is approximately the cut-in velocity for most small wind turbines, and that is the wind velocity at which the turbine starts generating electricity. Map 2 shows the solar resource considering the terrain altimetry and the buildings' influence (Fig. 10). The highest values correspond to a yearly GHI of 1422 kWh/m^2 (dark orange) and the lowest values to 783 kWh/m^2 (light green). To evaluate the wave energy potential along Cascais' coast, data was collected for 4 locations that are shown in Map 3 (Fig. 11).

The depth along the coast was also considered and is depicted in the green isobatimetry lines for 8, 16 and 30 m of depth, were the influence of the mouth of Tagus River can easily be seen.

The average annual power density for the wave energy at each location was obtained using the bivariate probability density function of power density and power direction, leading to a value of 26 kW/m for Cabo Raso, 19 kW/m for Guia, 26 kW/m for Cascais and 15 kW/m for Parede. The radial graphs corresponding to the 4 locations are show in Figs. 12-15.

3.2. Scenarios of energy demand in several sectors and GHG emissions

The scenarios' simulator has been used, and three different scenarios are studied. For this purpose, the year 2019 was selected as reference year, the most recent year with completed information that was not affected by the pandemic situation experienced in 2020/21.

The two first scenarios were chosen because the goals established in

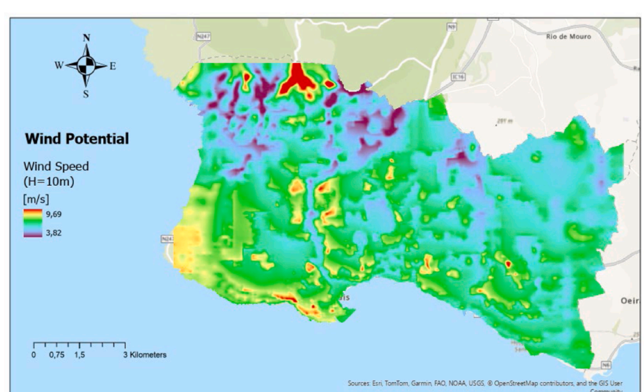

Fig. 9. Map 1 - Cascais' average wind speed at a height of 10 m above the buildings.

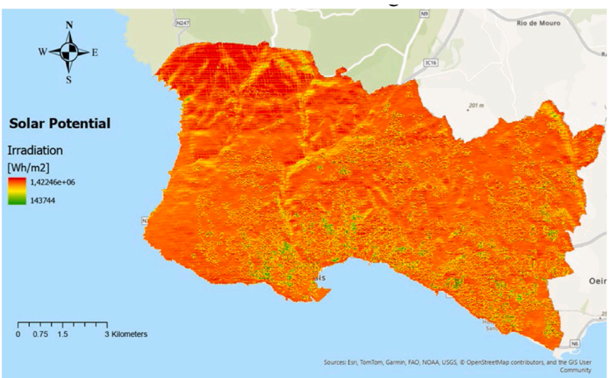

Fig. 10. Map 2 - Cascais' average yearly GHI considering the terrain altimetry and the buildings' influence.

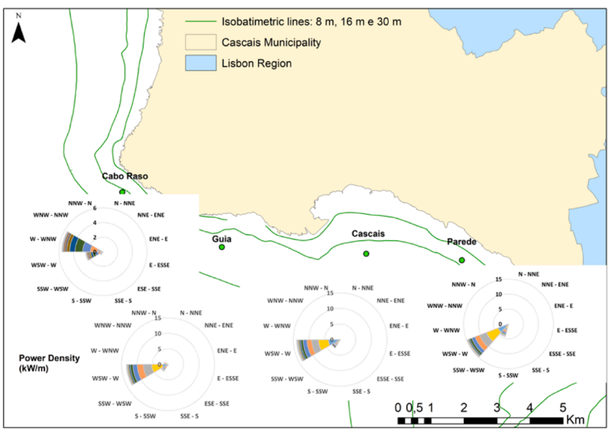

Fig. 11. Map 3 - Cascais' coast wave energy potential assessment locations.

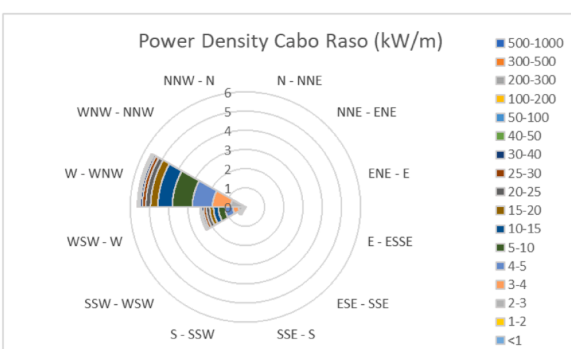

Fig. 12. Wave power density at Cabo Raso.

the first roadmap for 2050 developed for Cascais [33], foresee a BAU and a "High Development" scenario. But in this case, and especially motivated by the current global economic crisis that the majority of the countries all over the world are experiencing, it was decided to add a "Recession" scenario, especially relevant in the energy demand, that would allow to consider a slight decrease to the values of some of the simulated parameters, particularly in the amount of avoided CO_2 emissions, because Cascais' best predictions regarding this aspect, are a reduction of about 95 % of equivalent CO_2 emissions for the "High Development" scenario in 2050 when compared to the emission of 2015 [33].

For the future scenarios, the years 2030, 2040 and 2050 are considered regarding the evolution of the sector's energy demand in the municipality and subsequent GHG emissions. Based on the information available from 2011 to 2023 in the Portuguese databases of the National Statistics Institute (INE) [34], the General Directorate for Energy and Geology (DGEG) [35], PORDATA platform [36], the National Energy and Climate Plan 2030 [37], the Cascais Decarbonization Roadmap for 2050 [33] and the Cascais Climate Plan - Mitigation [38], the different scenarios were built for buildings, transports and industry. The graphs in Section 3.2.1 show the different variables that were analysed, Gross Domestic Product (GDP) per capita, population, inhabited residential buildings, electricity demand per capita, and final energy demand for the sectors mentioned in Section 2.2.2.

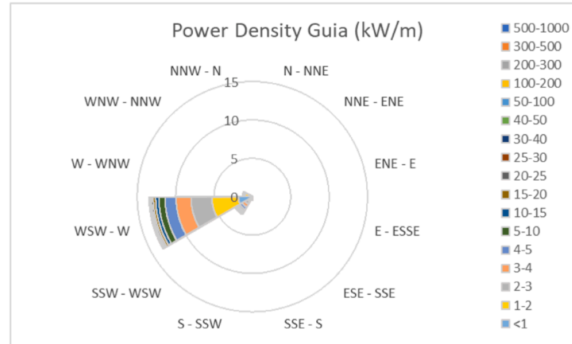

Fig. 13. Wave power density at Guia.

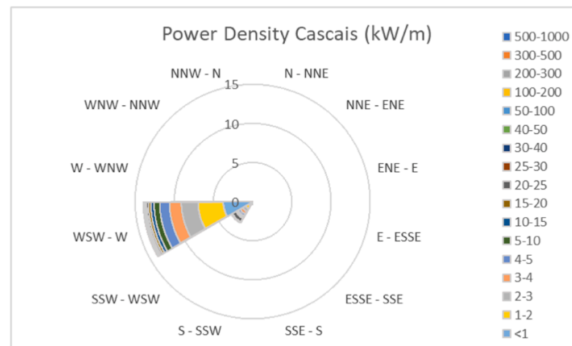

Fig. 14. Wave power density at Cascais.

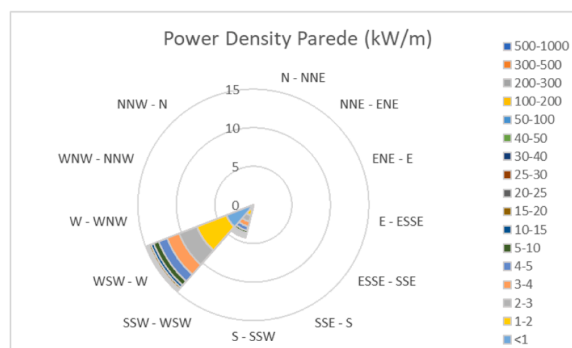

Fig. 15. Wave power density at Parede.

3.2.1. Socio-economic evolution in Cascais municipality

For the GDP, the population evolution, the inhabited residential buildings and the electricity demand, the information from previous years (2019, 2021 and 2023) along with the assumptions from Table 1 were considered to extrapolate for the future.

In the "High Development" scenario for GDP a yearly increase from 1.5 % to 2 % was considered (with a decrease of 2 % between 2019 and 2020 due to COVID pandemic), and as for the population, the yearly increase was from 0.5 % to 0.8 %. For the "Recession" scenario, GDP decreased yearly 0.75 % and the population from 0.2 % to 0.5 %, as shown in Figs. 16 and 17.

Considering the inhabited residential buildings, the yearly increase in "High Development" was from 0.8 % to 1.1 % and the yearly decrease in "Recession" was from 0.6 % to 1.2 %, Fig. 18.

The electricity demand has been growing steadily in the last few years, so yearly increase percentages were considered for both "High Development" and "Recession" scenarios, respectively, 1.5 % to 2 % and 0.3 % to 0.4 %, Fig. 19.

3.2.2. Energy demand and CO_2 emission evolution in Cascais municipality

In the reference year, 2019, the total final energy demand in the municipality was distributed in sectors as follows: i) 30.9 % in Residential; ii)18.5 % in Commerce and Services; iii) 1.2 % in Industry; iv) 47.1 % in Transport and v) 2.3 % in other sectors like water and wastewater, energy sector, public lighting and agriculture and fisheries. The demand per sector is affected by the socio-economic variables and its evolution according to the results obtained by the scenarization tool.

The demand per sector is affected by the socio-economic variables and its evolution according to the results obtained by the scenarization tool is depicted in Figs. 20–23. It is also important to compare the evolution scenarios with the CO_2 equivalent emissions, so the graphs show this information as well. As can be seen, the trend is always a decrease in emissions irrespective of which scenario is being considered, although, as expected, the emissions' decrease is higher in the "High Development" scenario. The increasing percentage of renewables in the Portuguese electricity energy mix, improved energy efficiency in buildings and in equipment, the increase of Electrical Vehicles (EV) usage, the penalties that will have to be paid for extra emissions, the international climate pacts that have been signed, the raising consciousness of the population, etc., create a large pressure for decarbonization.

In residential buildings, in 2021, 50.6 % of the energy demand was satisfied by electricity, 28.2 % by firewood and forestry waste, 14.3 % by natural gas, 3.7 % by propane and 3.2 % by butane [39]. This information along with Cascais historical energy demand data from DGEG was used as input in the scenarization tool to calculate the values shown in Fig. 19. It is expected that these percentages will shift in the near future with an even higher predominance of electricity in detriment of the use of biomass and natural gas.

Considering the natural characteristics of the municipality, tourism and local commerce are some of the most dynamic sectors in Cascais' economy. Nonetheless, the following subclasses of economic activities account for 49 % of the municipality's Gross Value Added (GVA): i) warehousing and transport auxiliary activities; ii) wholesale trade; iii) real estate activities and iv) head office and management consultancy activities. The final energy demand in commerce and services evolution for the three scenarios previously defined is depicted in Fig. 21.

The industry sector in Cascais is small when compared to the other sectors and that is why the final energy demand values are an order of magnitude lower than in the other sectors, as depicted in Fig. 22.

In the transport sector and according to the Strategic Urban Development Plan, the daily commutes in 2015 were distributed as follows: 66 % in private cars, 20 % in buses, 11,3 % by train, 11 % by walking, 2 % by bicycle and 1 % by shared scooter [40]. Presently, the transport modal distribution remains very similar, leading to the final energy demand in this sector shown in Fig. 23.

It is also noticeable that the greatest potential for reduction of energy demand and emissions lies in the residential buildings and transport sectors, irrespective of the considered scenario, as can be seen in Fig. 24.

In order to increase the detail of the analysis, total final energy demand, inhabitants' number, and GHG emissions spatial distribution in the three scenarios for 2030 per Cascais municipality parish are presented in Figs. 25–28. The parishes with the higher final energy demand are Cascais e Estoril with 2 458 TJ (High), 2 289 TJ (BAU) and 2 110 TJ (Low) and São Domingos de Rana, with 2 268 TJ (High), 2 112 TJ (BAU) and 1 947 TJ (Low), which also are the most populated, with 69 126 and 63 854 inhabitants respectively.

Regarding CO_2 emissions these two parishes are also the ones that produce more emissions, with 69 126 tCO_2e (High), 99 932 tCO_2e (BAU) and 107 070 tCO_2e (Low) for Cascais e Estoril and 63 854 tCO_2e (High), 92 220 tCO_2e and 98 807 tCO_2e (Low) for São Domingos de Rana in 2030.

The evolution of the total amount of CO_2 emissions in the municipality and the absorbed emissions of Land Use, Land-Use change, and Forestry (LULUCF) were also compiled to see how they compare to the

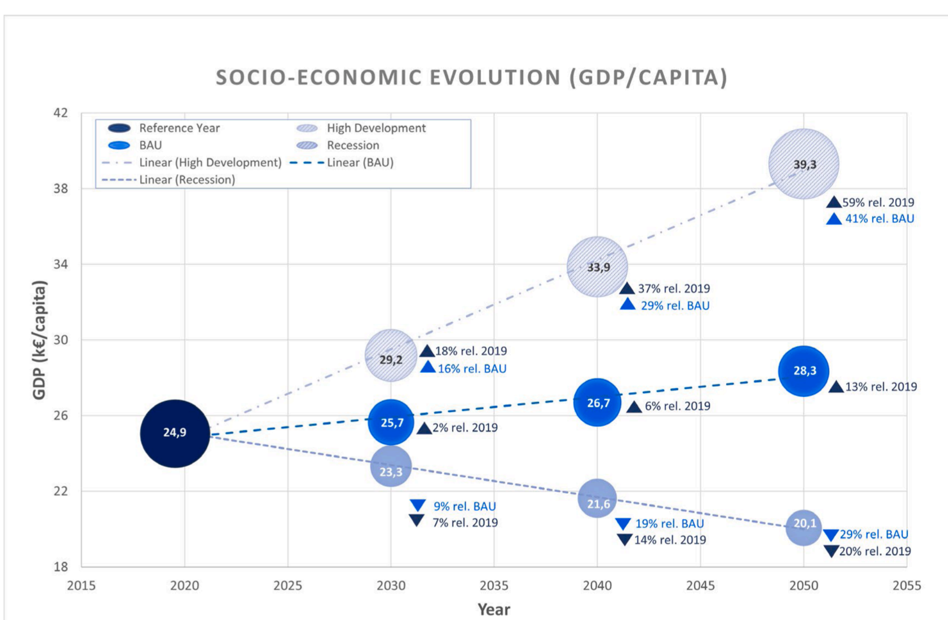

Fig. 16. Socio-economic evolution.

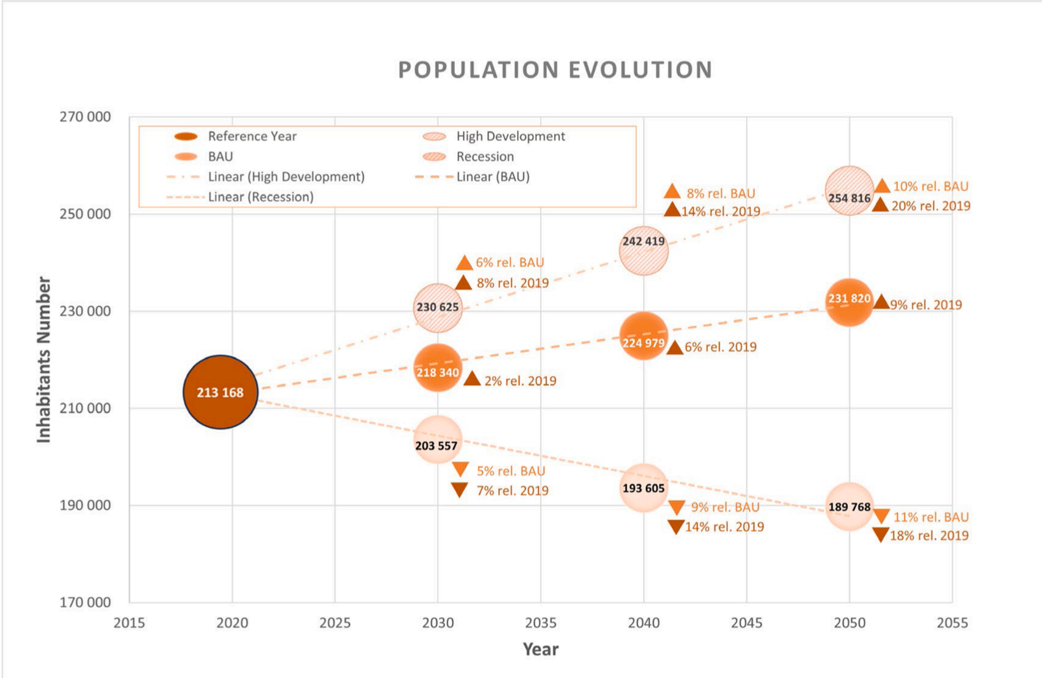

Fig. 17. Population evolution.

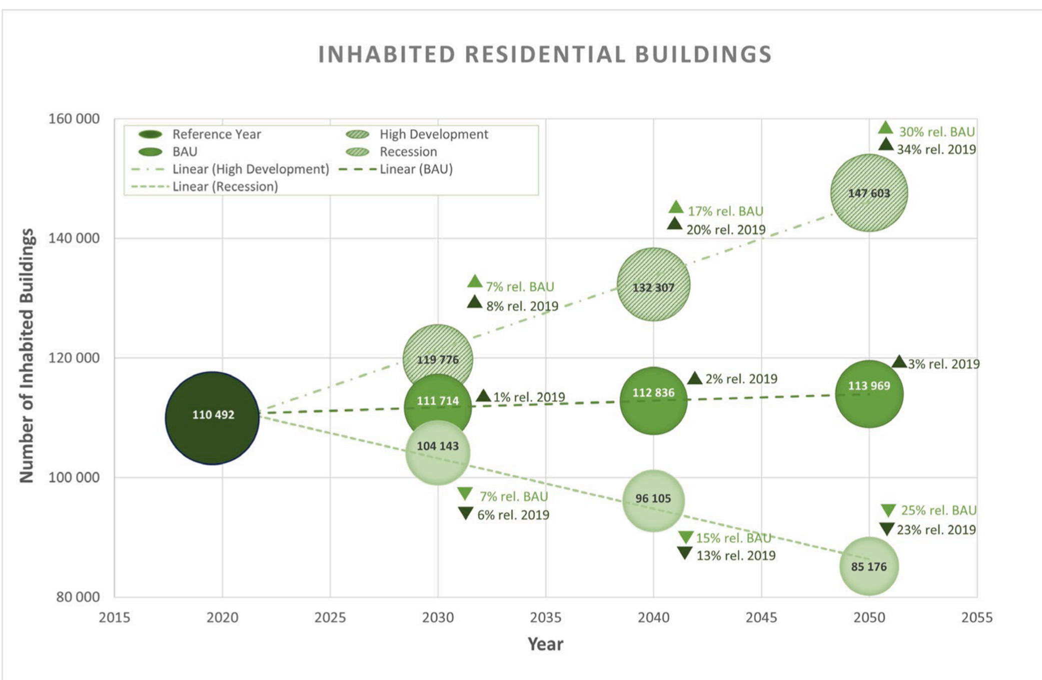

Fig. 18. Inhabited residential buildings evolution.

Cascais decarbonization goals by 2050, Fig. 28. The High Development scenario is the one that achieves a higher level of decarbonization by incorporating more renewable energy, increasing the transport electrification and use of hydrogen as fuel, and applying new, more efficient, technologies and equipment.

To increase the carbon sinks, the municipality will focus on 2 main measures, carbon sequestration by green spaces, and the emissions avoided by more fire-resistant forests. The implementation of these measures involves integrating these concerns into global planning and land-use planning instruments, as well as the active management of forests and green spaces, along with projects to renaturalise degraded areas and requalify watercourses and green spaces.

According to Cascais Climate Plan goals, emissions in the municipality by 2050 should be 66 ktCO_2e and considering the emissions in the High Development scenario and the absorption by the carbon LULUCF sinks, our work leads to the remaining emissions of 85 ktCO_2e, as shown in Table 2. Cascais Climate Plan used data from 2015 and had the assumption that in 2050 the municipality would have 214 147

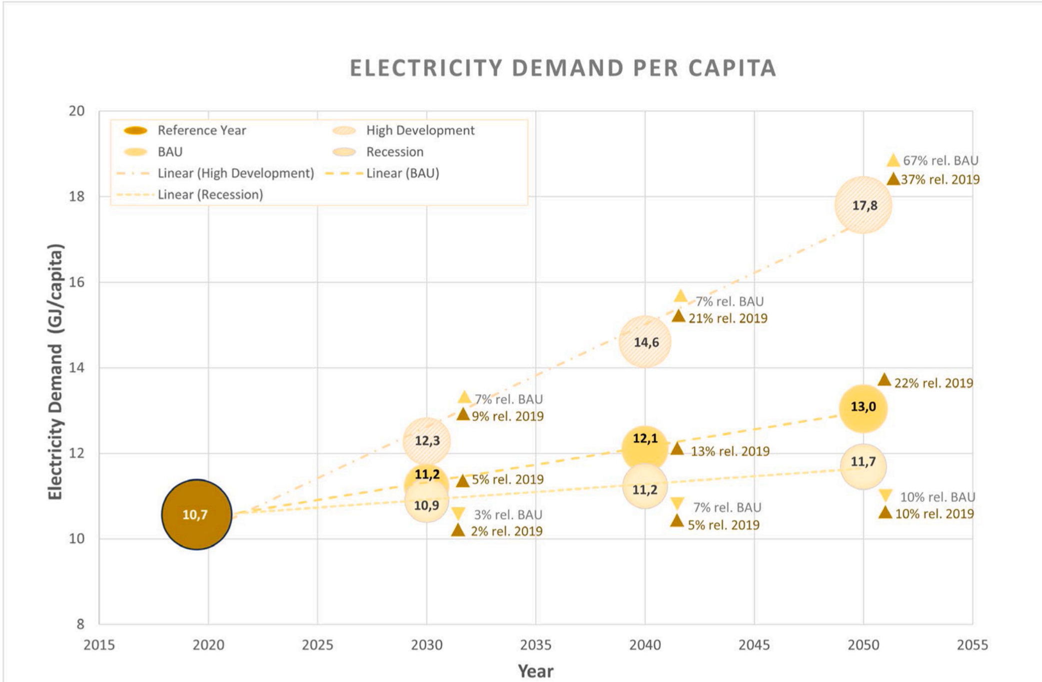

Fig. 19. Electricity demand evolution.

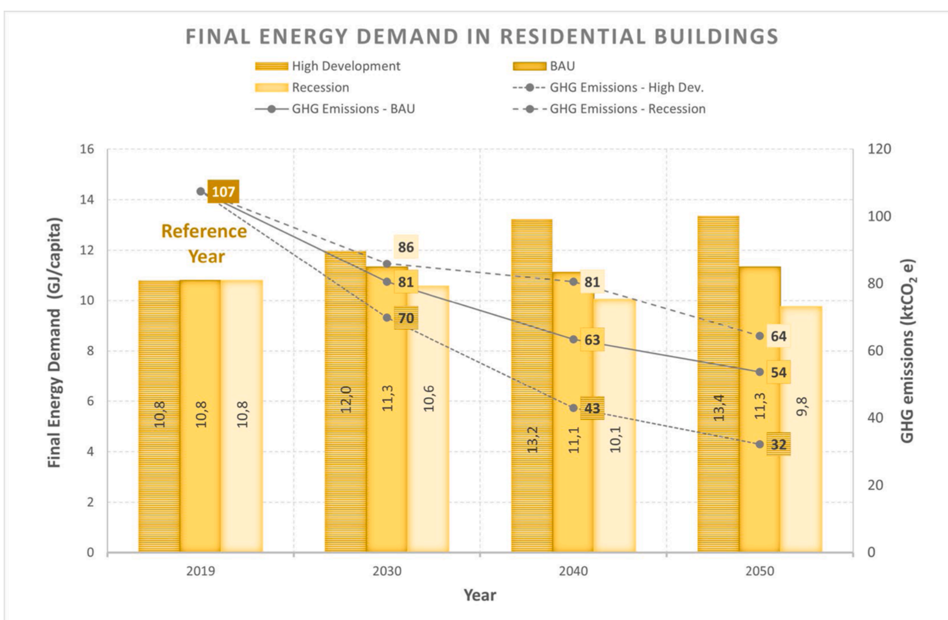

Fig. 20. Residential buildings' final energy demand.

inhabitants, when in fact, that number was already surpassed in 2023, with 219 636 inhabitants. In the last 10 years the population in Cascais has been growing at an average rate of 1 % each year, except for 2020 and 2021 due to the COVID pandemic and between 2022 and 2023, that had a growth rate of 2 %. Considering this data, it is not expected that in a High Development scenario the population will decrease by 2050. In order to accommodate this change, the values have been adjusted and that explains the difference in values.

The increase of Renewable Energy (RE) generation will help reduce emissions in all sectors and can be especially beneficial when implemented as distributed generation for self-consumption and in renewable energy communities, lowering grid losses due to the decrease of energy flow, contributing to more community cohesion and the reduction of energy poverty. Fig. 29 shows the expected final energy demand, the contribution of fossil and renewable energy and the renewable energy share for each sector in 2030. Observing this figure, it is very evident that the transports sector, with a 96 % share of fossil energy is the one that needs more decarbonization intervention measures.

Cascais has a commute transport modal distribution with a share of 66 % for personal vehicles and 20 % for public transportation [40]. There is already a free municipal network of buses, and the municipality is developing a project of a station to produce hydrogen from urban

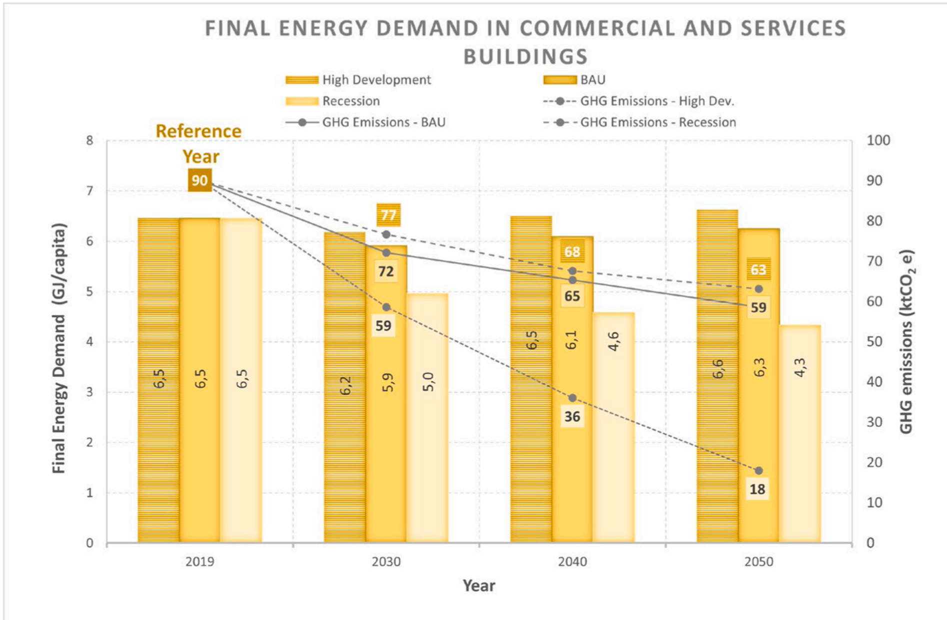

Fig. 21. Commercial and services buildings' final energy demand.

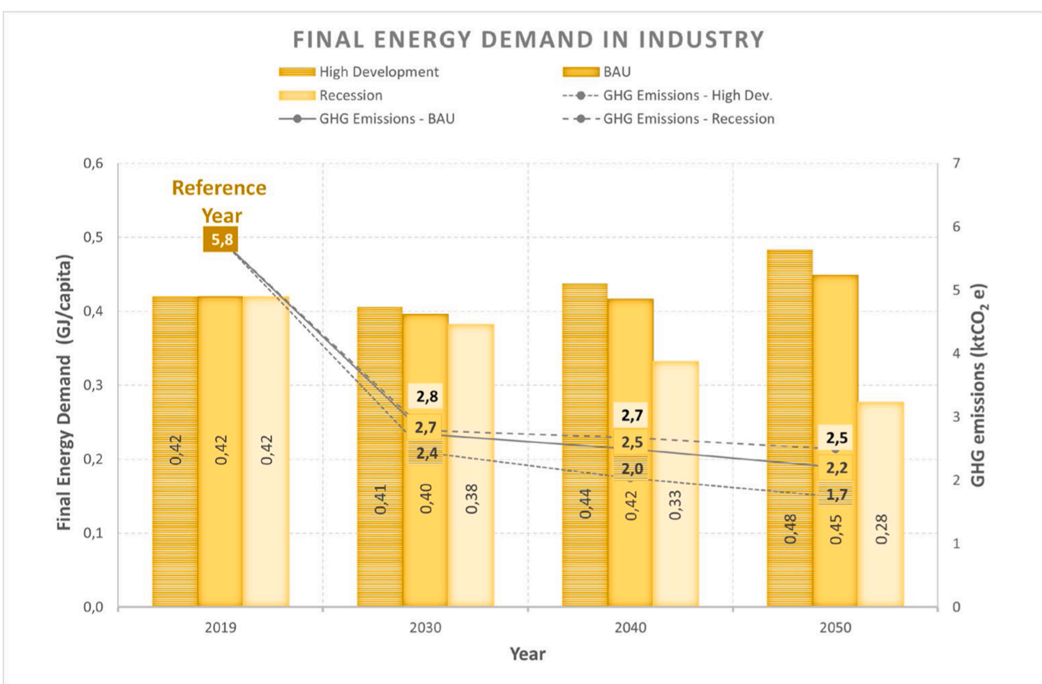

Fig. 22. Industry final energy demand.

waste and intends to gradually convert all municipal buses to hydrogen. The station will have the capacity to produce up to 389 kg of hydrogen per day, of which only 100 kg are needed to supply the daily public transport operation, the surplus can be used by the municipal fleet or sold.

Regarding electric vehicles, Cascais has 147 charging stations with a total of 251 charging plugs and has recently opened a public procurement tender to install 100 more charging stations. The higher availability of charging stations can be an incentive for citizens to use electric or hybrid vehicles and decarbonize their daily commutes. As for soft mobility, the municipality aims to increase cycling routes by another 100 km and promote parking (for bicycles, scooters and cars) near train stations.

4. Conclusion and future work

This paper presents the preliminary work developed so far in the scope of the *Re*-Value project focussing on the implementation of the project's objectives in one coastal city located in Portugal - Cascais. The main highlights go to the strategic goals of this follower waterfront city, it's RE potential assessment and the first outcomes from a dedicated tool that was used to analyze the development scenarios in the Energy and

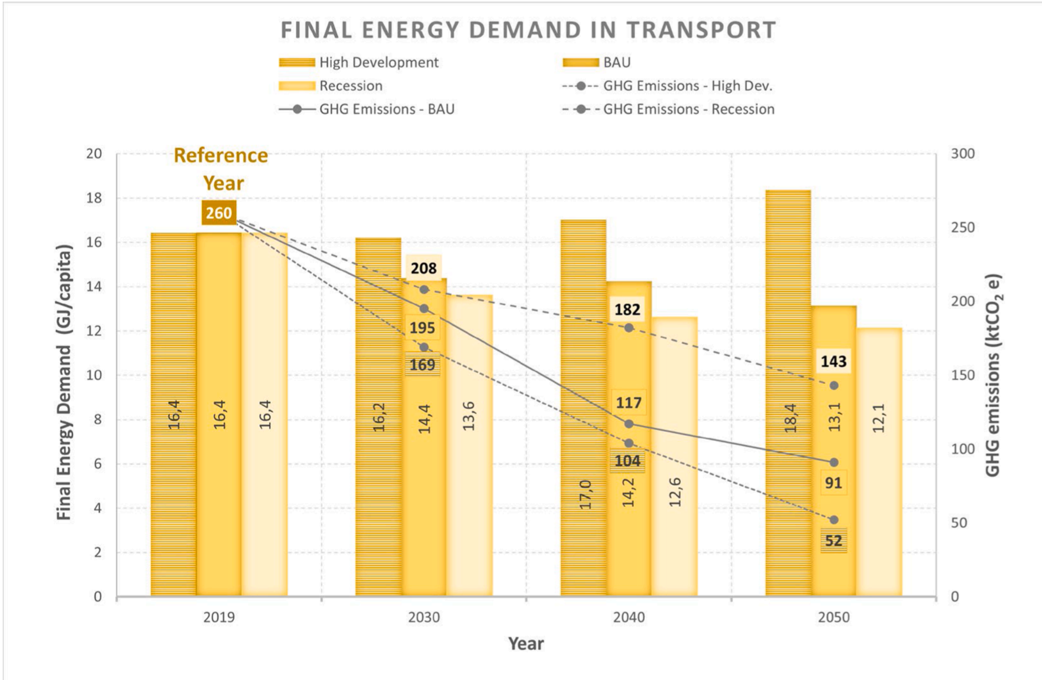

Fig. 23. Transport sector final energy demand.

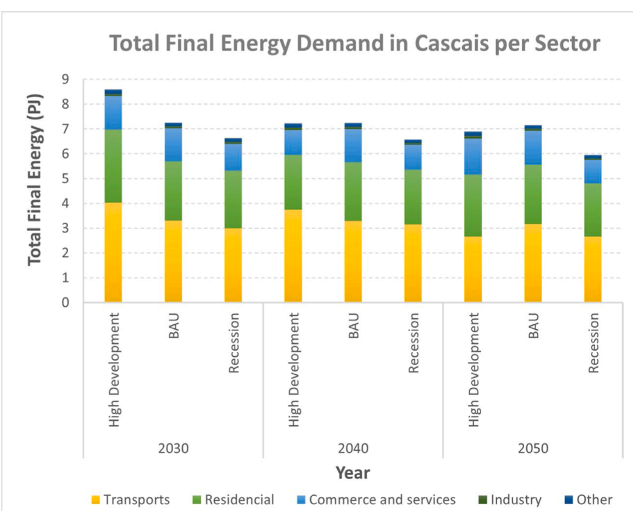

Fig. 24. Final energy demand evolution divided by sectors in the 3 scenarios.

Transport sectors. An innovative and simplified Decision Support Tool (DST) was developed and applied to assist in the design of these scenarios and trajectories, which are now being integrated into the climate neutrality roadmap for Cascais.

The DST's specific design offers practical advantages that directly address key gaps in existing municipal-level climate action planning tools. Its integrated simplicity is tailored for municipalities with limited resources, enabling effective use without requiring extensive technical expertise or costly infrastructure. The phased scenarization-mitigation-mapping approach provides a clear, step-by-step process that facilitates manageable implementation and continuous progress tracking. Moreover, the DST's direct use of official national and local data ensures accuracy, relevance, and alignment with policy frameworks, enhancing decision-making confidence. Together, these features make the DST a more accessible, efficient, and context-sensitive tool compared to more complex alternatives, empowering municipalities to take timely and informed climate action.

The DST tool results show that in the High Development scenario, when compared with the reference year of 2019, the total final energy demand can decrease by 7.2 % in 2050 due to the implementation of energy efficiency measures following the concept "Energy Efficiency First" and along with the increase of electrification, the introduction of hydrogen in the transport sector, and a broader implementation of renewable energy in the urban fabric and public spaces, Green House Gas (GHG) emissions can decrease by 82 % in 2050.

This will allow the municipality to implement priority mitigation measures focused in these sectors, like the improvement of the energy efficiency in buildings, starting with municipal buildings, disseminate information about how citizens can have access to funds for the improvement of their houses' energy performance, facilitate the use of public transport (the city already has 44 municipal bus lines that are free for city inhabitants, workers or students) and alternative means of transport, other than a private vehicle in daily commutes, give incentives to electric or hybrid vehicle users, like free parking in certain city areas, etc.

According to the results obtained in this phase of the project, it is possible to conclude that the city (and the whole municipality) is characterized by a high renewable potential, especially for the development of solar PV projects. In terms of the pilots' location, and when looking in detail to what was proposed in the scope of this project, the use of renewable energy systems for the electrification of the majority of the activities, has a large potential in the pilot areas, some possibilities are the installation of PV car parking shading systems with charging stations for electrical vehicles and PV bench shading with plugs for cell phones or other small appliances in Carcavelos beach and Guia coast, and PV charging stations for electrical bicycles and scooters in Ribeira das Vinhas cycle lane. The expansion of these strategies to other areas beyond these pilots should also be considered.

The Decision Support Tool (DST) developed in this study was intentionally designed to be simple and accessible, particularly for municipalities with limited technical or financial resources. While it offers valuable guidance, the results are based on general assumptions and aggregated data, and should therefore be interpreted as indicative rather than as precise forecasts. The tool was applied in the specific

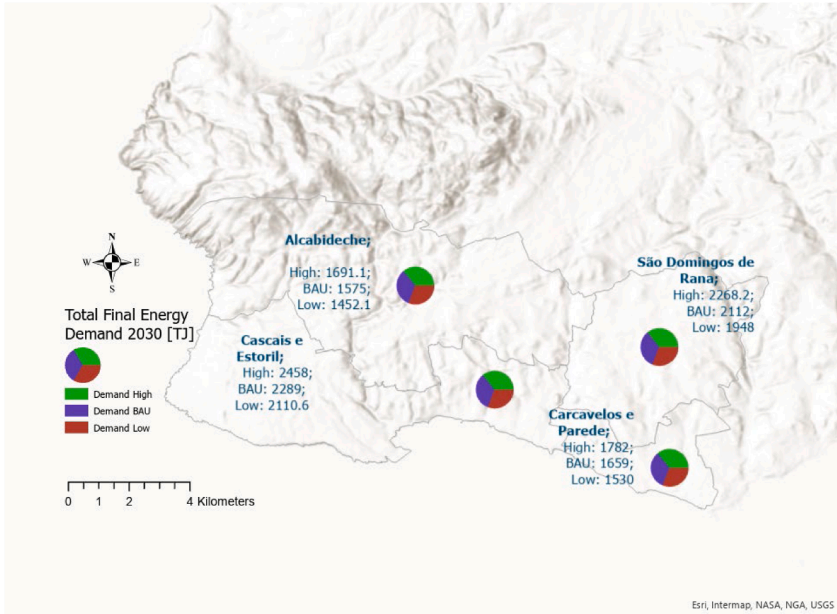

Fig. 25. Final energy demand in residential buildings, for 2030, per parish.

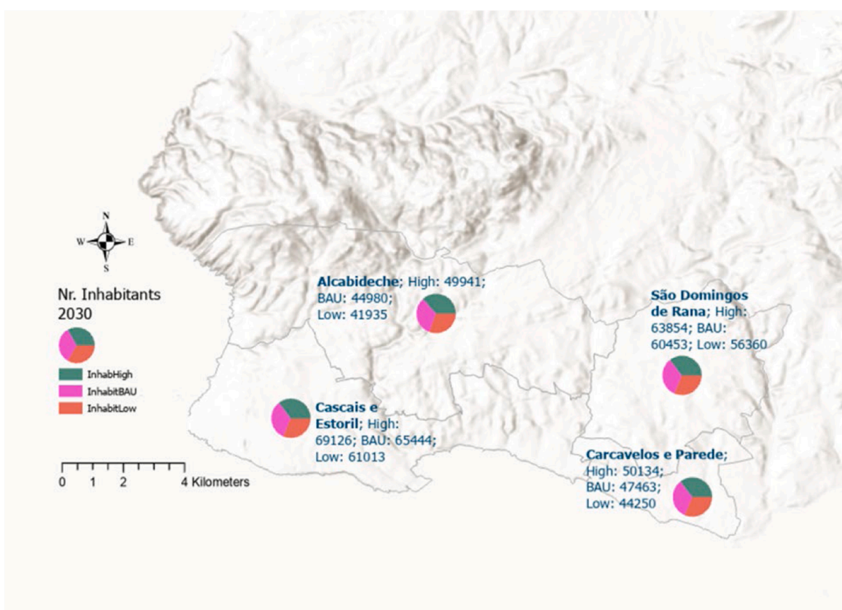

Fig. 26. Nr. of inhabitants, for 2030, per parish.

context of the municipality of Cascais; as such, some outcomes may not be directly transferable to other cities without appropriate contextual adjustments. In certain instances, the limited availability of data necessitated the use of estimates, which may affect the precision of the results. Nevertheless, the DST serves as a practical and user-friendly instrument to support the development of climate neutrality roadmaps.

The input database used by the tool was compiled by the authors using publicly available raw data from official Portuguese sources, covering all municipalities in Portugal. This data was reformatted to enhance usability and to align with the analytical needs typical of decarbonisation roadmap development. The current scenarisation component of the tool has certain limitations, primarily due to uncertainties associated with input assumptions and the absence of a fully developed mitigation module. This missing component, which is still under development, is intended to assess the impact of individual mitigation measures on final energy demand and greenhouse gas (GHG) emissions. It is expected to be completed by the end of the project (December 2026) and will serve as a key enhancement to the DST, improving its robustness and analytical depth in future applications.

As future work, the second phase of the roadmap will be developed. This includes the analysis and proposal for mitigation solutions using DST mitigation simulator. Additionally, citizen engagement actions are planned in order to communicate and validate/update the mitigation measures. The results from all developing roadmaps belonging to the *Re*-Value project cities will be analyzed in the so called “Community of Practice” and according with the *Re*-Value Impact Model and the EU Cities Mission. In the last stage, each city will update their long-term Territorial Transformation Plans to accelerate their journeys to climate

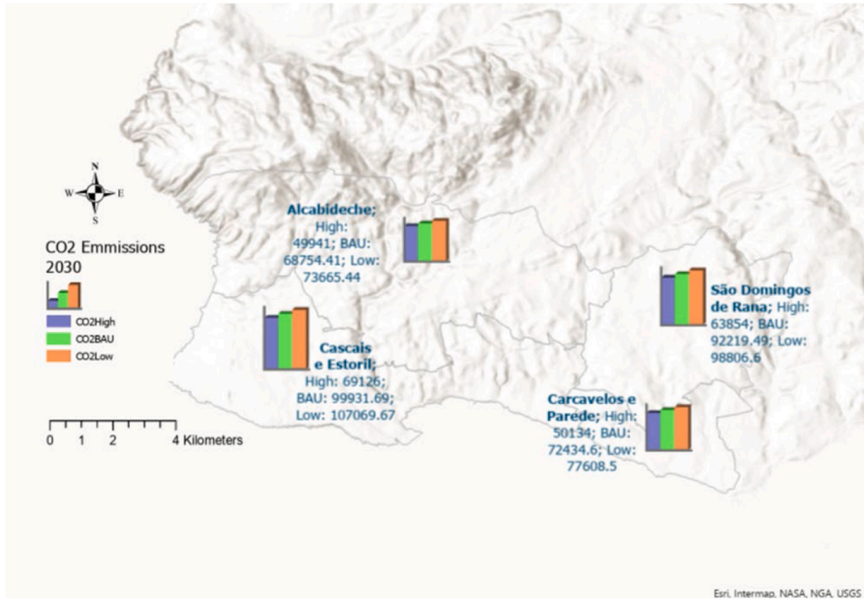

Fig. 27. CO_2 emissions for 2030, per parish.

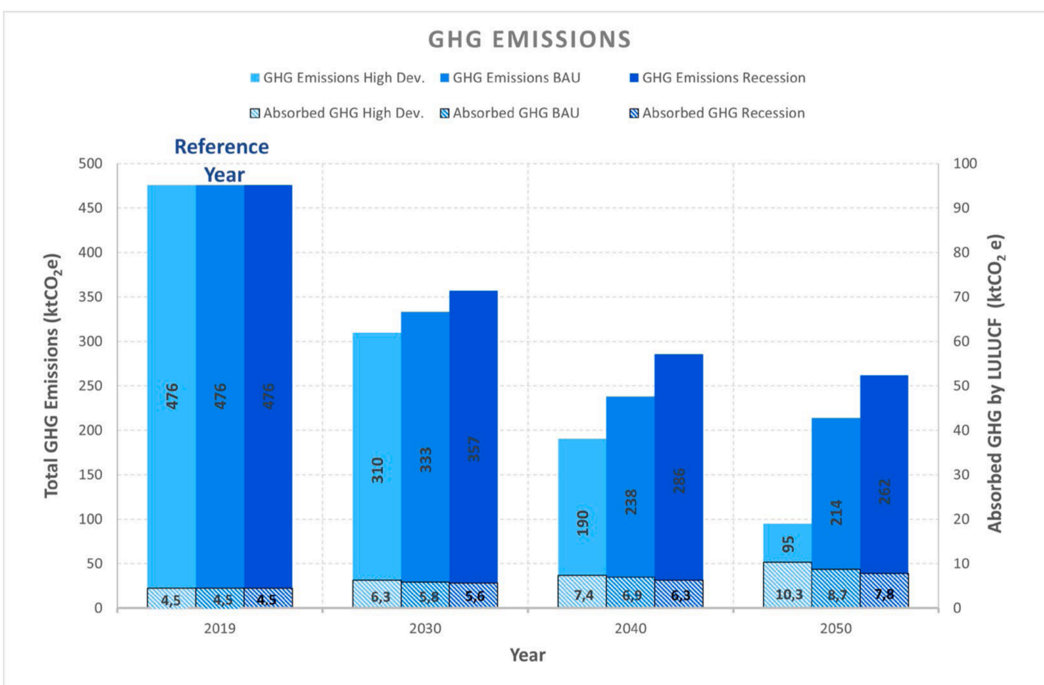

Fig. 28. Total GHG emissions and GHG absorbed by LULUCF evolution in the 3 scenarios.

Table 2
GHG emissions evolution and comparison with Cascais Climate Plan goals.

	2019	2030	2040	2050
Main 4 Sectors Emissions [ktCO_2e]	463.7	301.4	185.5	92.7
All Emissions [ktCO_2e]	476.2	309.5	190.5	95.2
LULUCF absorbed emissions (High Development scenario) [ktCO_2e]	4.5	6.3	7.4	10.3
Remaining Emissions [ktCO_2e]	471.7	303.3	183.1	85.0
Goals Cascais Climate Plan [ktCO_2e]		297.0	231.0 – 165.0	66.0

neutrality by latest 2050.

CRediT authorship contribution statement

L Aelenei: Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **S Viana:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **T Simões:** Writing – review & editing, Resources, Formal analysis, Data curation. **F Amorim:** Software, Formal analysis. **S G Simões:** Software, Formal analysis. **J Barbosa:** Software. **P Justino:** Software, Formal analysis. **H Gonçalves:** Writing – review & editing. **J Dinis:** Resources. **G Fernandes:** Resources.

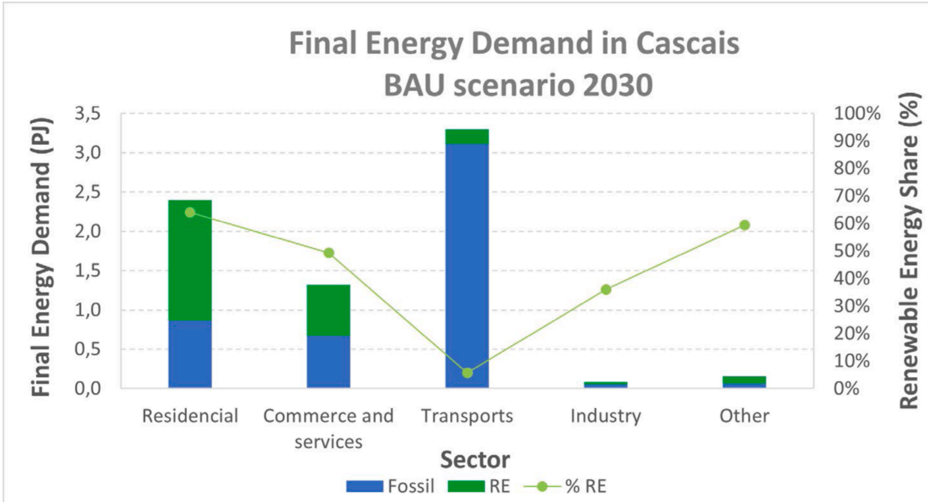

Fig. 29. Final energy demand per sector and renewable energy share (2030).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

LAURA AELENEI reports financial support was provided by National Laboratory of Energy and Geology. If there are other authors, they 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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Data availability

Data will be made available on request.

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