



Can net-zero carbon be a cost-effective enabler of water and energy self-sufficiency?

Luís P. Dias^{*} , Júlia Seixas

CENSE – Center for Environmental and Sustainability Research, Department of Science and Environmental Engineering, NOVA School of Science and Technology, NOVA University Lisbon, 2829-516 Caparica Portugal

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ABSTRACT

Water and energy services are key for cities' healthy development, but their integrated management has been limited. Cities decarbonization requires fully integration of water and energy systems to prevent policies and solutions with limited benefits or even with negative trade-offs. Municipal water-system (i.e. water supply, consumption and wastewater) was integrated into the energy-system optimization model (TIMES_CityWE) to get explicitly connected water and energy flows and technologies. Optimal water-energy system configurations to deliver water and energy services for Cascais municipality in Portugal were generated up to 2050, with the goal to assess if and how net-zero carbon target and resources' prices may act as enablers of local resources cost-effectiveness. Net-zero goal leads to efficient technologies, delivering 16% less water and 20% less energy consumed in the residential sector in 2045, compared with the absence of net-zero target. Notably, water efficient technologies show cost-effectiveness to reduce both water and energy consumption, while enhance resource self-sufficiency. Achieving net-zero carbon in 2045 requires a reconfiguration of the current energy system with 33% of the total final energy demand and 26% of water demand fulfilled by local sources, a significant increase from 2015 (6% and 13% respectively), clearly demonstrating net-zero carbon targets serve as enablers of water and energy self-sufficiency. Integrated water and energy systems modelling captures combined positive effects to optimize future configurations, providing support to better local policies.

Introduction

Half of the world's population is concentrated in urban areas [1], making them hotspots of water and energy consumption, accounting for two thirds of global final energy consumption [2,3]. Urban areas are true engines of the world economy [4,5], as they generated up to 82% of the global Gross Domestic Product in 2013 [6]. Cities have been responsible for multiple environmental impacts, directly or through their supply chains. Around 70% of global CO₂ emissions is attributed to world urban areas [6], and water demand in cities is expected to increase by 80% by 2050 [7,8].

Cities have a key role to advance on the transition towards zero carbon economies and support national climate commitments [9]. European cities are making significant progress in climate change adaptation and mitigation planning [10–12]. Currently around 65% of these cities have implemented mitigation plans. The planned climate mitigation actions claimed by cities can imply a significant GHG emission reduction by 2050, representing 27% reduction for the EU as a whole

[12–14].

Population growth coupled with increasing urbanization areas and climate change impacts are challenging water cycle sustainability [15], exacerbating water scarcity in cities, as showed by He et al. [16]. Innovation in water resources management and policies is essential to ensure water services for both population and economies. Measures such as desalination provides a critical solution to water scarcity, its energy-intensive nature necessitates a careful examination of associated trade-offs [17]. A holistic perspective, considering both energy and water systems, may prevent climate mitigation pathways to hamper other sustainability criteria [18–20] and leverage synergies towards multiple goals [21]. The nexus approach to water and energy systems requires to take specific urban sustainability conditions [22,23].

Energy system modelling tools at the city scale have increased to assess local climate mitigation and urban planning [24,25]. Nevertheless, modelling the water and energy system components and their interactions is increasingly relevant [26,27], and remains a research challenge [28], mostly if considering very detailed spatial scales

^{*} Corresponding author.

E-mail address: luisdias@fct.unl.pt (L.P. Dias).

[29,30].

These challenges are also closely linked to the multi-level policy landscape on sustainability and climate action. There is a strong need for research to support sustainable development [31], particularly by considering the interconnectivity of the various Sustainable Development Goals (SDGs) [32]. In particular SDG 11 (sustainable cities and communities) is highly dependent on the objectives of SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy) [33].

At the urban level, Portuguese municipalities play a crucial role in implementing integrated water-energy strategies. However, challenges remain in articulating water and energy policies at the local scale, particularly in ensuring coherence between national decarbonization goals and municipal climate strategies [34]. This study contributes to this policy discussion by integrating water-energy interactions into a city-scale optimization model, providing insights to enhance local resource self-sufficiency while supporting national climate commitments.

The relevance of energy consumption to manage water scarcity in cities and the net-zero ambition justifies the development an integrated water-energy optimization model, including detailed representations of all water and energy systems components from supply to demand sectors and all points of resource use intersection at the city level. We expand the energy system optimization TIMES model to include water flows and technologies to analyse, through scenarios analysis, how carbon neutrality target in 2045 may act as a driver to cost-effective water and energy technologies and to increase local resources self-sufficiency. This research advances the state-of-the-art with the following contributions:

- Water and energy integrated flows and technologies at the city level are taken explicitly (i.e. through technical and economic parameters), using the IEA-ETSAP TIMES energy modelling framework, to optimize the combination of technological solutions and endogenous resources towards net-zero carbon goal.
- Intertwined conditions between energy and water systems for net-zero carbon goal in 2045, focusing on resources self-sufficiency, are explored for local policies.
- Combined (positive and negative) effects of the energy and water resources use, technologies and measures, greenhouse gases (GHG) emissions reduction and cost minimization contributes to the water-energy nexus discussion at the city level.

This paper follows with section 2 with a brief overview of the case study and water and energy system conditions, and a description of the new TIMES model expanded with water reference system (TIMES-CityWE) and scenario assumptions. The modelling results are reported and discussed in section 3 and concluding remarks are provided in section 4.

Methods and data

This section presents the methodology used to assess how net-zero carbon target in 2045 may promote the cost-effectiveness of new water and energy technologies and the self-sufficiency of local resources, describes the model and its features, the case study and the scenarios to generate future pathways for the city water and energy systems configuration.

Case study

Cascais municipality is located in the Lisbon region (Portugal) with an area of 97,40 km² and 210 361 inhabitants in 2015 [35], corresponding to a population density of 2 160 hab/km². The territory has an important coastline facing the Atlantic ocean, and is a remarkable spot of tourism, with a varying population in half of the year with more 170 tourists per 100 residents [36]. Cascais has one of the highest solar radiation levels in Europe [37,38], providing exceptional conditions for

using solar PV and solar thermal technologies. The region has a very high risk to climate change impacts [39], such as heat waves, droughts intensity and frequency increase [40] and sea level rise [41]. These impacts have direct effects on the energy supply and demand and water availability and quality, with significant economic impacts [42], representing additional pressure on vulnerable families.

Water to supply Cascais municipality comes mostly from one main source located in the Tagus river basin, outside the municipality frontier (i.e. imported water) with a historic ratio between water consumption and renewable water resource (e.g. water exploitation index) of 46%, which is expected to intensify under climate change scenarios [43]. The municipality has two main water extraction points (endogenous water), one superficial and other groundwater, equipped with different treatment systems [44]. The water system for Cascais municipality representation (Fig. 7 in cf. supplementary information), shows that supply is more than 86% coming from external and 70% of water consumption is allocated to households.

Regarding Cascais energy system (Fig. 8 in cf. supplementary information), energy consumption is dominated by fossil fuels, accounting for 60% of the total final energy consumption, electricity for 28% and only 6% for renewable energy sources (i.e., biodiesel, bioethanol and biomass). Transport is the key energy consumer (48% of the total), followed by residential (30%) and services buildings (16%).

The municipality has been actively engaged in promoting energy efficiency and innovative sustainable solutions in the last decade, intending to assist citizens and stakeholders to reduce energy costs and engaging in new technologies. Cascais is a signatory of Covenant of Mayors for Climate and Energy since 2009, and renewed the 2030 goals, i.e. reducing at least 40% the GHG emissions by 2030[45], published its roadmap towards carbon neutrality until 2050[46] and adopted a long-term Adaptation Action Plan (2017). Also noteworthy is the Local Energy Strategy with a 10-year implementation period, under development, to increase energy efficiency and renewable energy sources. Climatic characteristics, potential endogenous energy and water resources, residents' socio-economic heterogeneity, and high energy and water dependence from the central grid are factors challenging the transformation of water and energy system configurations of Cascais in the future, to comply with bold sustainability commitments.

TIMES modelling tool expanded to include water components

Recent years have seen important advances in the development of integrated tools and models for assessing the interactions among resource systems [47,48]. Nevertheless, the majority are simulation-oriented, leaving a gap for optimization-driven frameworks [49] capable of endogenously generate systems combined configuration [50] to guide decision-making [51]. Moreover, several studies highlight the necessity to extend integrated systems modelling to the local scale [52], where resource interactions are particularly complex and policy-relevant [53].

The Integrated MARKAL-EFOM System models (TIMES) generator was developed under IEA-ETSAP [54], to generate future configurations of the energy system, optimizing the overall system cost, while comply with a set of constraints [55,56]. The TIMES model has been used at the national scale [55,57,58] and applied at the city scale [59–62]. Data availability and quality are challenges for urban energy system modelling [63], requiring additional efforts.

Although there is a significant margin for improvement [64], the energy system modelling at city scale, particularly using TIMES model, has showed progressive robustness. Comodi et al. [65] evaluated the effectiveness of local-scale energy policies in households, transport and the public sector, through three energy scenarios by applying the TIMES model generator for Pesaro, a seaside municipality in central Italy. In addition to providing important insights on policies for curbing fossil fuel consumption, the study proved the adequacy of the TIMES model as a robust tool to analyse the dynamics of a municipal scale energy system,

further confirmed by Lind & Espegren [66] and Di et al. [24]. The former applied the TIMES model to analyse low carbon pathways for the city of Oslo, demonstrating the usefulness of the model for testing individual measures to facilitate the design of policy instruments, while the later used the TIMES model to define comprehensive climate mitigation strategies on the medium-term in a region in southern Italy. TIMES model at city scale has been recognized as a powerful tool to deal with system complexity and provide robust assessment of local energy sustainable transition [59,67].

The inclusion of water system components in the TIMES model began with the work of Dubreuil et al. [68] and Bouckaert et al. [69], who expanded the world energy model – TIAM-FR model [70] to explicitly represent water demand and analyse integrated changes in water and energy processes. The combination of water and energy systems into a single bottom-up technology-oriented energy model allows, for example, to assess how much electricity is required for future water demand. Nevertheless, it is worthy to mention the end-use technologies databased was limited and no water-energy connections at city scale and demand side sectors were fully considered.

Similarly, a study conducted for China [71] applied the TIMES-ChinaW, a water-smart energy model considering water supply and demand of the energy sector. The water-energy nexus in China was assessed, with a focus on water withdraw for different energy generation technologies and didn't cover non-energy water uses or end-use sectors. Ahjum et al. [72] changed the South African TIMES model (SATIM) to include water abstraction and consumption by different processes and technologies for the whole country. The SATIM-W model focuses on the water needs for electricity generation and recognized the requirements to represent endogenously the end-use sectors' demand for water. More recently [73], developed an additional module for TIMES regional model with the inclusion of non-energy resources associated with agriculture activities, namely water, fertilizers and pesticides and respective outputs of food and biomass. The expanded TIMES-WEF model was customized and calibrated to the agriculture system of Basilicata region, and the results illustrated the importance to consider non-energy components, as water, to fully understand how agriculture system may evolve in a cost-effective way. Sehn & Blesl [74] included water demand for cooling for electricity generation technologies, water for irrigation of energy crops (e.g. biomass) in the TIMES Pan EU to assess how the German energy transition implies changes in the water system.

This study introduces a novel local-scale TIMES model that endogenously integrates water and energy systems within an optimization framework, enabling detailed assessments of cost-effective, net-zero pathways for municipal water-energy systems.

TIMES_cityWE model description

The Water-Energy system model (TIMES_CityWE) was developed, by expanding the TIMES model at city level [59,62] to integrate the detailed components of the local water system. The model optimizes the total energy and water system in order to minimize the total system cost, while deliver the required energy and water services (both estimated exogenously). TIMES is a technical–economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. A reference case estimates of end-use energy service demands (e.g., car road travel; residential lighting; steam heat requirements in the paper industry) are provided by the user. In addition, the user provides estimates of the existing stock of energy related equipment in all sectors, and the technical (e.g. efficiency, lifetime) and economic (e.g. investment costs) characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials. Using these as inputs, the TIMES model aims to supply energy services at minimum global cost (more accurately at minimum loss of surplus) by simultaneously making equipment investment and operating and primary energy supply and energy trade

decisions, by region [70].

The inclusion of water system impacts the minimization costs by adding new energy needs and resource availability constraints that linked, directly or indirectly, with energy systems functions. Fig. 1 presents an overview of the energy and water systems components and connexions considered in the TIMES_CityWE model. The model was developed to explore how Cascais municipality may undertake a transformation to become a net-zero carbon region, taking the energy and water endogenous resources.

The TIMES_CityWE model employs 2015 as the base year and was calibrated against historical based on water and energy consumption official data (calibration results detailed in [supp. materials](#)). It was assumed a maximum deviation error of 10% between model results and historic data for the different energy sources and water consumption by sector. The model time horizon covers till 2050, divided in periods of five years, with a yearly temporal resolution of 18-time slices, representing 3-day hourly time steps (Day, night and peak) for two representative 3-day (week and weekend) and three different seasons (summer, winter and other season, corresponding to spring and autumn). Spatial coverage includes the administrative boundary of the case study (Cascais municipality) and split into four regions corresponding to parishes. TIMES_CityWE includes energy and water commodities trade between these regions. The model considers end-use sectors, disaggregated as shown in Fig. 3, with a higher detail in residential buildings (11 typologies) and transport sector, due to its importance in urban energy and water consumption.

The model integrates the energy and water systems by connecting both system components within the municipality administrative boundaries. Examples include energy consumption by water treatment and wastewater units, and electricity demand of desalination units. Energy and water imported from outside municipal boundaries are imports with no relation between them. TIMES_CityWE model include water system key components and connections (Fig. 9 in [cf. supplementary information](#)) from supply resources and processes to end-user's demand.

Energy services demand

The TIMES_CityWE model takes the energy services demand, estimated exogenously, for the end-user sectors (e.g. passenger (in [p.km](#)) and freight (in [t.km](#)) for mobility, useful energy for space heating and cooling, specific electricity for lighting) within the city boundaries. The corresponding final energy consumption was calibrated with local statistics. For the case of transport, indicators of energy purchased within the municipality were used, meaning transport activities from adjacent municipalities or passing through traffic is excluded.

Regarding residential buildings, 13 typologies are considered, 11 referred to existing buildings, and two to new apartments and new detached houses, taking features like building constructive characteristics and occupants demographic and socio-economic conditions ([cf. supplementary information](#)). Energy services demand per typology were estimated based on a detailed assessment of energy performance of dwelling stock [75] and from residential buildings energy performance certificates [76]. Water heating demand by typology considered the socio-economic characteristics of households, as family size and occupants' age which impacts water consumption [77]. Energy services demand projections took the evolution of the number of dwellings and the population projection (Fig. 14 in [cf. supplementary information](#)) for the municipality, resulting in a ratio of 0,52 dwelling per inhabitant by 2045. Total energy demand is projected to increase 2% in 2050 for residential buildings and 3% for mobility, in comparison with 2015.

Water services demand

Water services demand until 2050 was detailed for the residential sector, taking into consideration different types of end-uses as listed in, for the different building typologies. Due to scarce information for the case study, the water demand per end use was derived through country

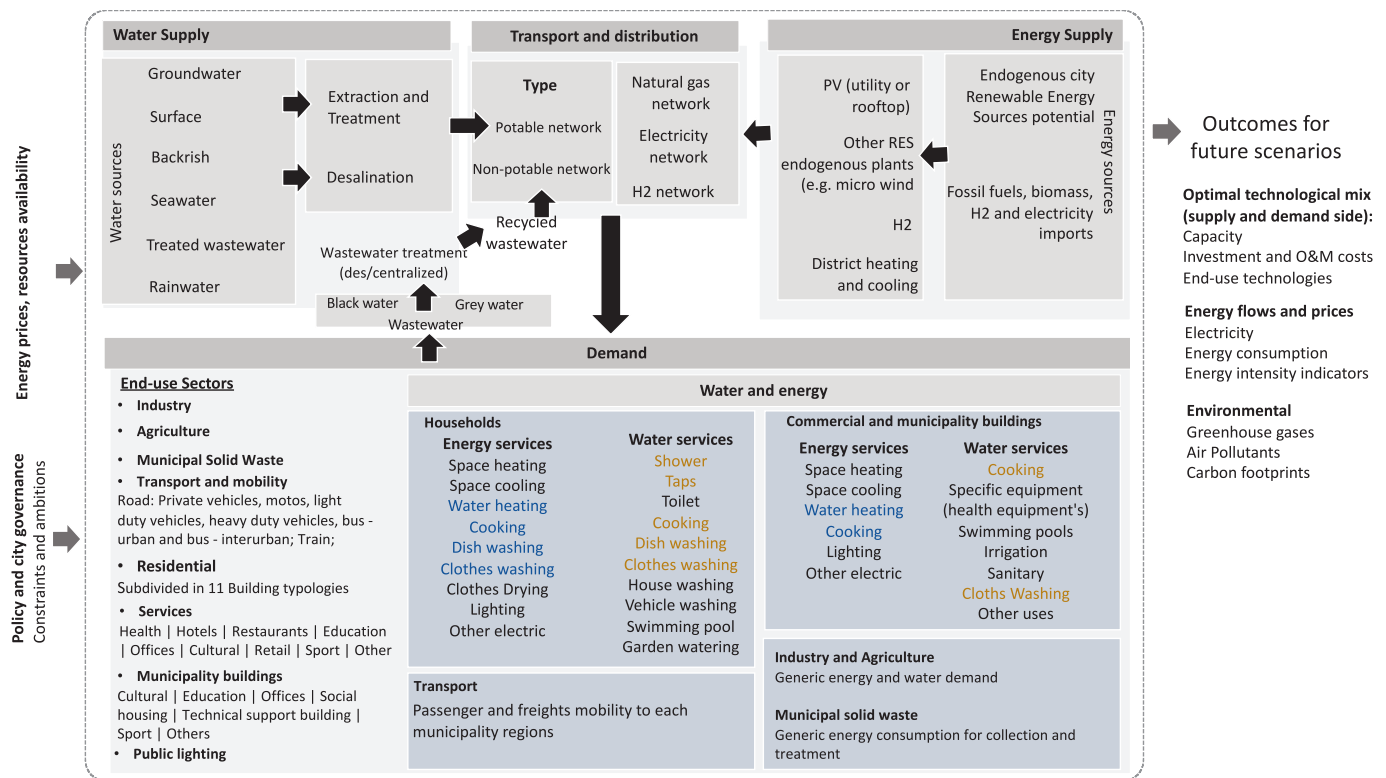


Fig. 1. TIMES_CityWE model overview with water and energy supply, transport and demand components. Energy services (in blue) with a direct connection with water. Water services (in orange) with a direct connection with energy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicators [77–79], associated with the correspondent households’ residents socio-economic characteristics. Water demand was projected through the number of households and population, as for energy services. Total water demand is projected to increase 23% in 2050, and 2% for residential buildings, in comparison with 2015. For the remaining sectors, a generic approach was applied due to data constraints, resulting in total water demand per sector. Table 5 (in supplementary information) presents the current water demand by end use and building typology, as detailed in the TIMES_CityWE model, varying from 146 L per capita per day in old buildings to 221 L in new buildings.

Endogenous energy and water resources potential

Endogenous renewable energy resources are available and vary along the territory [80], and municipalities can use them to meet, at least partially, energy needs[81] and GHG mitigation efforts. Endogenous energy resource in Cascais municipality was assessed considering key infrastructure (e.g. buildings type and available and suitable rooftop area) and resource availability and characteristics (i.e. wind speed and variability). The techno-economic potential of solar PV was based on buildings’ features, both in rooftop and façades for decentralized PV systems, and on land use for utility scale systems. Typology TP9 is the champion for solar PV potential as it corresponds to 34% of total buildings, followed by TP6, TP7 and TP8 with high rooftop area (average 118 m²/building) representing 50% of total buildings. Cascais municipality has high urbanization fabric with very fragmented rural areas which limits utility scale solar PV, as well as wind turbines, since the foundations need at least 9 m³ [82]. Solar endogenous potential was estimated for each parish, after the methodological approaches and results from [83–88], totalling almost 350 MW (Table 3 in c.f. supplementary information).

Wind resources were not considered because micro wind turbine is not an option due the low capacity factor, low wind velocity and frequency and thus low cost-effectiveness [89], and also due to factors as

audio-aesthetics, health, and safety [90].

Offshore technologies, as wave and wind energy, despite the high resource potential in the coastline [91], were not considered due to the focus on decentralized local technologies and to the high conflict with other relevant local economic activities, such as fishing [92] or tourism [93]. Biogas production from municipal wastewater treatment was assumed to be fully used in the facility [94], and is negligible from the municipal solid waste, because existing landfill is closed and there is no biogas recovery. The biomass used in residential sector for space heating is assumed from external sources, because local biomass is from a forest with legal protection restrictions. The biomass from waste/residues doesn’t have significant potential use.

Endogenous water sources include groundwater and surface water, rainwater harvesting (RWH), grey wastewater reuse and treated wastewater use. Local RWH potential (Table 3 and Fig. 15 in c.f. supplementary information) was assessed using the methodology outlined in ETA0701 [95] and in Silva et al. [96], which takes into account a combination of factors, such as the precipitation pattern, along with the area available for rainwater catchment on residential buildings. The collected rainwater is used for non-potable uses only in the residential sector, with technical and economic parameters from Silva et al. [96]. Although high potential for RWH was recognized within the service sector, particularly in retail [97], this potential was not considered due to lack of data and information required to support the assessment.

The recovery of treated wastewater for non-potable applications was taken as an option for water endogenous availability, and its technical and economical parameters [98] were included in the model technology database. Currently, a centralized wastewater treatment plant is in the municipality, that already uses part of the treated wastewater volume for own operational needs. Additionally, the municipality uses this water for street cleaning and public spaces irrigation. Decentralized treatment systems of grey wastewater is included in the model database, in accordance with Zhang et al. [99], who suggest feasible applications,

being its technology techno-economic characterization based on Arden et al. [98].

The various types of determinants of water loss [100] were not possible to include in the model solutions portfolio due to limitations on detail information for technical and economic characterization. Therefore the reduction of water network losses considered the apparent losses component, i.e. due to erroneous meter readings or unauthorized consumption, due to its high benefits [101], by using 7% and with no investment cost.

Energy and water technologies

The TIMES_CityWE model runs over an extensive database of technology options on energy and water supply and energy and water end-using, all of them characterized by technical (e.g. capacity factor), and economic parameters (e.g. investment cost, variable cost) along the time period of modelling (i.e. from 2015 up to 2050), through the respective cost learning curve. Due to the importance of the residential and transport sector for the urban case study, technology options for these sectors are taken in a very detailed fashion. The database supporting TIMES_CityWE model includes around 160 energy technologies (e.g. solar PV rooftop, internal combustion and electric vehicles, washing machine categories according to energy efficiency labels (Table 6 and Table 7 in supplementary information) and 10 different water technologies (e.g. desalination plants).

Scenarios

The modelling exercise aims to study the impact of net-zero carbon emissions in 2045 and energy and water resources pricing on the long-term water-energy interconnected systems configuration, while delivering the required energy and water services up to 2050. Four scenarios were taken in TIMES_CityWE model, to assess how net-zero carbon target, energy and water price increases impact the adoption of endogenous resources and technologies. Table 1 presents the four scenarios, namely its different characteristics and purposes.

The reference scenario (REF) sets the base case trajectory of the evolution of the local water-energy system, with no GHG target, aiming to assess the cost-effectiveness of technologies to deliver the projected services demand. Three more scenarios consider the introduction of progressive conditions: (i) Cascais NetZero Carbon (CNZC), with a GHG emission target (reduction of 40% of GHG emissions in 2030 compared with 2015 and net-zero in 2045, in line with Portuguese climate framework law); (ii) CNZC_ELC+, with doubling the imported electricity

price from 2030 onwards; (iii) CNZC_WAT+, with doubling the imported water price from 2030 onwards (Fig. 8 in cf. supplementary information).

The national power system is under deep decarbonization, and the carbon intensity of the electricity in the national grid will likely decrease up to 2050. For this exercise, two carbon emission factors were considered from the current 314 gCO₂/kWh in 2015: 5 gCO₂/kWh in 2050 in the REF scenario, as expected from the country long-term cost-effectiveness of renewables; 2 gCO₂/kWh in the CNZC scenarios, aligned with the national carbon neutral target in 2050 [102].

Results

First, section 3.1 establishes the baseline performance by analysing cost-effectiveness of energy and water systems under no mitigation objectives (REF scenario) driven solely by cost-optimal technology choices. Section 3.2 examines the energy system transformation under deep decarbonization objectives. Section 3.3 analyse the effects of two resource cost variation on technology deployment and water and energy systems configurations. Section 3.4 synthesises energy-water intertwined effects across all scenarios, which demonstrates cross-sectoral synergies through specific quantifying integrated performance metrics including self-sufficiency levels.

Cost-effectiveness of energy and water systems under no mitigation objectives

Although there is a slight increase in pressure on the local municipality energy and water systems to deliver services, with a 2% increase in energy demand and 5% in water services demand by 2050 compared with 2015, we may still expect an increase on the cost-effectiveness of water and energy technologies. The year 2015 is used as the base year for results analysis, as it represents the energy matrix produced by the municipality, whereas 2020 is considered a non-representative due to the covid-19 lockdowns.

Results show that GHG emissions in the municipality can decrease up to 73% from 2015 to 2050 under the REF scenario (Fig. 2), with 53% of this reduction attributed to direct GHG emission (scope 1). This decline is driven by (i) reduction of the energy consumption (16%) (), promoted by the adoption of energy-efficient technologies, such as electric vehicles and energy-efficient households appliances; (ii) electrification increase, from 32% in 2015 to 40% in 2050; (iii) decline in fossil fuels consumption from 62% in 2015 to 37% in 2050, with natural gas

Table 1
Prospective scenarios characteristics assessed with TIMES_CityWE.

Scenario name (code)	Scenario key characteristics			Scenario purpose
	GHG emission target	Electricity price (as imported from the national grid)	Water price	
Reference (REF)	No	Electricity price according with the <i>Long-term Strategy for Carbon neutrality of the Portuguese Economy by 2050</i> (as in APA [102])	Water price reference trajectory after an escalation factor of 2,5% by Boyano & Moons, [103]	Explore the optimal cost-effective city water-energy system configuration (endogenous resources and technologies), with no emissions constraint.
Cascais NetZero Carbon emissions (CNZC)	Local <i>Fit for 55</i> targets: equivalent to a reduction of 40% of GHG emissions in 2030/2015 and net-zero carbon (scope 1 and 2) in 2045 in line with Portuguese climate framework law [104]	Electricity price according with the <i>Long-term Strategy for Carbon neutrality of the Portuguese Economy by 2050</i> (as in APA [102])	Water price according with REF scenario	Assess the impact of carbon deep decarbonization on the local endogenous energy and water resources
CNZC plus increase of imported electricity price (CNZC_ELC +)		100% increase relative to CNZC values from 2030 onwards	Water price according with REF scenario	Assess the impact of high electricity pricing imported from the national grid on the adoption of endogenous renewable energy sources
CNZC plus increase of imported water price (CNZC_WAT +)		Electricity price according with the <i>Long-term Strategy for Carbon neutrality of the Portuguese Economy by 2050</i> (as in APA [102]).	100% increase compared with REF scenario, from 2030 onwards	Assess the impact of high-water price imported from outside the city on the adoption of local endogenous water solutions

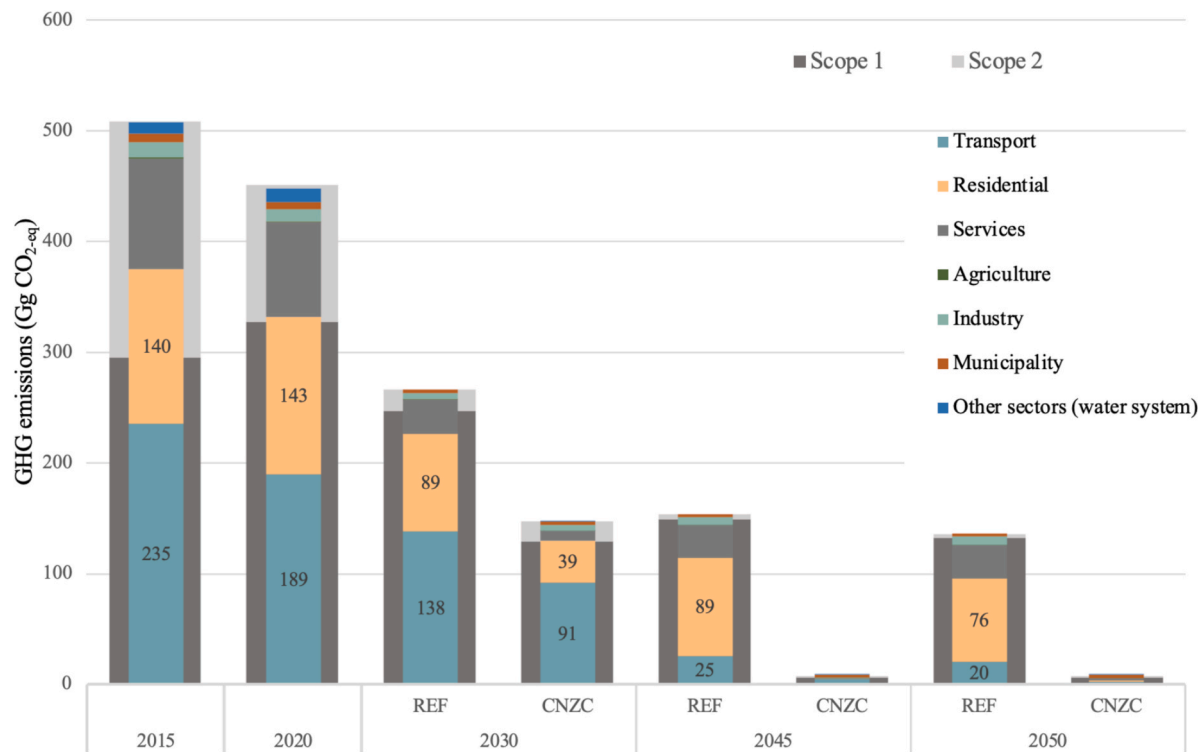


Fig. 2. GHG emission per sector for the REF and CNZC scenarios (Emissions from industrial processes, land use and land use changes and from municipal solid waste sector are not included).

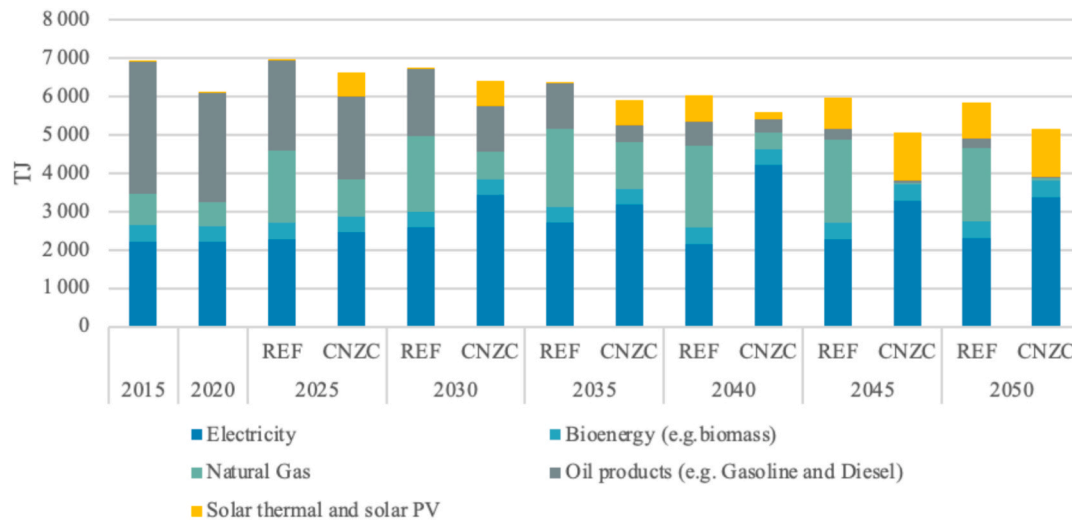


Fig. 3. Total final energy consumption per energy source in Cascais municipality for REF and CNZC scenarios.

remaining dominant in buildings; and (iv) a rise in the share of renewables in the energy mix, reaching 23% in 2050, driven by solar PV technology. These factors justify the increase of Cascais energy self-sufficiency, which improves from 6% in 2015 to 23% in 2050.

For both residential and commercial buildings, indicates a 49% increase of final energy consumption, mainly due to the increase of energy demand in services and households. In the absence of a mitigation target, natural gas continues to play a significant role up to 2050, limiting the potential for electrification. GHG emissions in 2030 are projected to be half than in 2015, with this trend persisting until 2050, driven primarily by households (−15% between 2030 and 2050), then with smaller reduction in services (−3%). However, this decrease is predominantly in Scope 2 emissions due to national grid’s electricity

decarbonization trajectory, whereas Scope 1 emissions increase due to the continued reliance on natural gas.

Regarding the transport sector (), electrification emerges as a cost-effective option even in the absence of a mitigation target, given the high efficiency of electric cars to deliver mobility. This shift leads to a significant reduction of 78% of the final energy consumption in 2050 compared to 2015, along with a 41% decrease in GHG emissions by 2030, reaching near-zero GHG by 2045. Beyond large-scale electrification, passenger shared vehicles also appear as a cost-effective preference.

Model optimization for the selection of cost-effective technologies also influences water system, resulting in a 16% reduction of total water consumption in the municipality by 2050 relative to 2015 (Fig. 4).

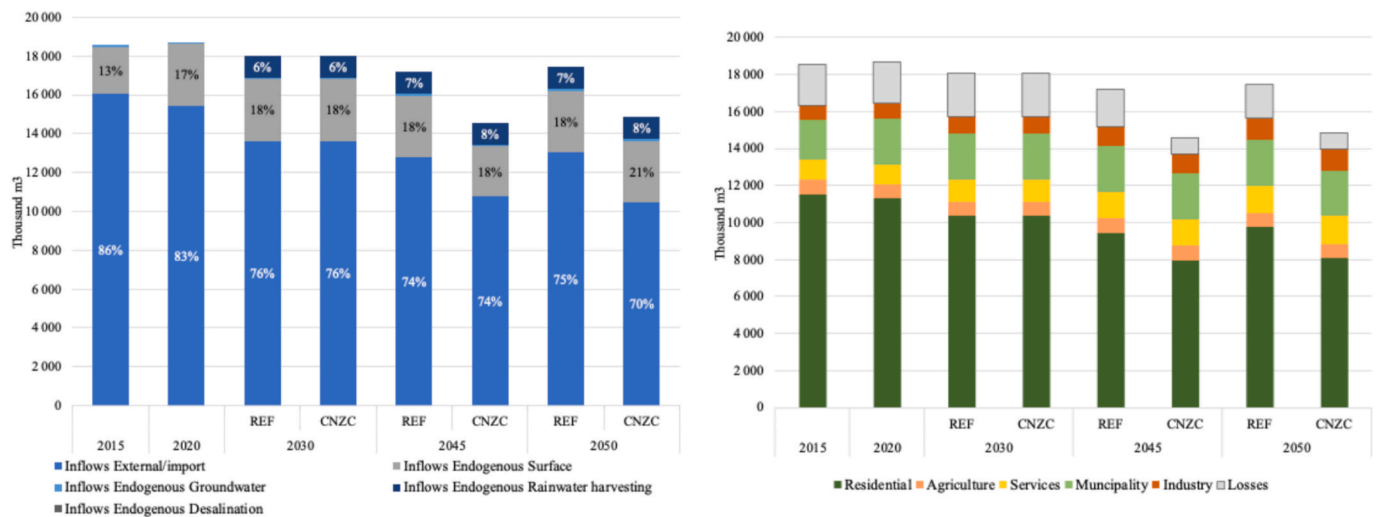


Fig. 4. Cascais municipality water sources (left) and water consumption per sector (right) in REF and CNZC scenarios.

Water-energy-efficient appliances in the residential sector, combined with rainwater harvesting solutions, contribute to reduce water imported from outside the municipality and minimize the electricity consumption for water transport and distribution. Consequently, municipal water self-sufficiency reaches 25% in 2050 compared with 16% in 2015. However, decentralized grey wastewater reuse technologies are not selected due to their high energy consumption.

The transformation of the energy and water systems under the REF scenario is solely determined by the cost-effectiveness of available technologies in the model database. TIMES model operates under a perfect foresight condition, meaning it considers long-term information (e.g. declining technologies costs) to inform short-term decisions. Although recognizing the relevance of other societal factors in energy system modelling [105,106] the current model version, and study scope, does not include, for example, household budget limitations, or social acceptance, or willingness to pay/adopt solutions. Therefore, results serve the purpose as an exploratory tool to identify optimal technological options for delivering energy and water services at minimum system cost.

Energy system transformation under deep decarbonization objectives

The CNZC scenario shows both 2030 GHG reduction target (40% compared to 2015) and 2045 net-zero carbon emissions objective in Cascais are achievable (Fig. 2). Scope 1 emissions reduce almost to zero, with final energy consumption run mostly by electricity and solar PV (Fig. 3), the key role in achieving climate targets [107]. Electrification of the end-uses reaches 65% in the municipality in 2045, with the renewables in the final energy consumption representing 33%. Endogenous energy sources represent more 27% in 2045, when compared to 2015. Moreover, mitigation in 2045 in Cascais also benefits from the decarbonization of national power system (scope 2), with a carbon intensity factor of 1,7 gCO₂/kWh. This shows the municipality as free-rider of national efforts to decarbonize, in line with Laine et al. [108], with measures adopted outside the jurisdiction of the city, outsourcing the responsibility for actions to either private properties or national actors with broader boundaries. This also underscores the enhance the municipality's climate policy, particularly the Cascais Carbon Neutrality Roadmap [46], by intensifying the objectives to increase local renewable energy sources.

Under CNZC, decarbonization of the transport and buildings sector will likely intensify in the short-term, with emissions reduction of 61% and 81% respectively in 2030 compared to 2015. The main driver in both sectors is a massive introduction of electric technologies, increasing the share of electricity in the total energy consumption in 80% in

buildings and 91% in transport sector, in 2045 (Fig. 11 and 12 in c.f. supplementary information). The adoption of electric vehicles starts more intensely in 2030 in CNZC (than in REF), representing 32% of total energy consumed in transport sector. Hydrogen becomes a viable source for heavy passenger and freight vehicles, representing 1% of the total transport energy consumption in 2045, following other city studies, as Malmo [109]. Also, shared vehicles to supply short distance passenger mobility in urban context are significantly adopted, accomplishing 20% of mobility demand in 2045, as supported by Fidanoglu et al. [110] and Zhang et al. [111]. Results show the impact of a deep transformation of vehicles stock on energy consumption (less 80% between 2015 and 2045) and on the system overall GHG reduction.

Similarly, achieving the net-zero target drives a higher electrification rate in households, contributing to a further 20% reduction in total energy consumption by 2045, compared to the REF scenario. This effect is already evident by 2030, due to the technology replacement pace (e.g. natural gas is replaced by solar and electricity for water heating and cooking) in the short-term, resulting in approximately 5% less energy consumed compared with REF scenario. The progressive introduction of more efficient technologies more than compensates the increasing demand for energy services.

Regarding the water system (Fig. 4), decentralized grey wastewater treatment is implemented in 2045 in CNZC scenario, accounting for 13% of total households water consumption. This highlights the benefits of using treated grey wastewater for residential non-potable needs, leading to a reduction in water and energy consumption associated with the conventional water supply sources. Mitigating water network losses also contributes to lower water consumption levels by 6% in 2045 in CNZC, compared to 12% levels in 2015. Additionally, rainwater harvesting potential is fully utilized in this scenario, and the adoption of high-efficiency water-energy appliances results in a 21% reduction in residential water consumption.

Compared with REF scenario, setting a net-zero carbon target in 2045 boosts the transformation of the water-energy nexus system as follows: (i) efficient and electric technologies become competitive earlier, as example for electric vehicles and cloth and dishwasher appliances, accelerating electrification from 38% to 65%, in 2045; (ii) endogenous resources use increase and is anticipated, extending self-sufficiency from 21% to 33% in 2045 for energy and from 25% to 26% for water (as of Table 2); (iii) earlier competitiveness of solar thermal and of decentralized grey wastewater to supply households non-potable uses.

Table 2
Energy and water self-sufficiency levels in all scenarios analysed and energy and water use decrease pattern along the modelling period.

Scenario	2015	2020	2030	2045	2050	Δ2045 vs 2015
	Energy self-sufficiency					Energy use
REF	6,0%	6,3%	6,7%	21,0%	23,4%	-14%
CNZC			16,8%	33,1%	32,5%	-27%
CNZC_ELC+			22,2%	33,1%	34,2%	-27%
CNZC_WAT+			16,8%	33,1%	32,5%	-27%
	Water self-sufficiency					Water use
REF	15,9%	15,9%	24,5%	25,6%	25,3%	-7%
CNZC			24,4%	26,1%	29,7%	-21%
CNZC_ELC+			24,5%	26,1%	29,7%	-21%
CNZC_WAT+			24,1%	26,1%	29,7%	-21%

Cost increase of electricity and water from sources outside the municipality

We intend to understand if and at what extent the increase of the energy and water costs acquired outside the municipality, while comply with a net-zero goal in 2045, may impact the future configurations of the local water and energy systems. Higher imported electricity cost (scenario CNZC_ELC +) induces the reduction (-11%) in electricity use from the national grid, which is compensated with early introduction of endogenous renewables for electricity production, notably solar PV, reaching 18% of total electricity production in 2030 Fig. 5. The high deployment of solar PV in the municipality doesn't consider other socio-economic factors that influence adoption behaviour [105,112,113] such as household income availability [59]. Given the importance of solar PV, we done a sensitivity analysis scenario to evaluate the impact of a 10% increase in investment and operational costs. The results indicate that solar PV adoption remains similar to CNZC scenario (see [supp material table 8](#)). This highlights the relevance of solar PV to comply with local GHG emission targets [114].

The transport electrification rate has a low delay in 2030 in these scenarios compensated with a higher diesel (+30%) and gasoline (+7%) consumption. Similarly, in the building sector the electricity consumption reduction in 2030 induces a compensation with natural gas +6,6%. In the long-term, we observe no impacts on the endogenous vs. imported electricity. This is due to the strong influence of the net-zero carbon target on the fully implemented and local endogenous potentials and energy-efficient technologies.

Higher prices for water imported from outside the municipality (CNZC_WAT+) do not affect the local water-energy system configuration apart from the observed conditions in CNZC scenario. The condition to comply with the net-zero target induces the introduction of most options and available endogenous potential to reduce water consumption from external sources outside the municipality. In spite of this, desalination is not selected as an optimal solution for the municipality water system due to its potential increment in electricity demand [115], although it could contribute to higher water self-sufficiency [116]. The model result excludes this technology due to that the electricity increase may lead to a conflict in the provision of electricity to other sectors (e.g. transport and mobility) and undermine municipality decarbonization targets fulfilment.

Water from treated grey wastewater produced in households to non-potable uses is introduced in 2045, similarly as in the CNZC scenarios, which contributes to lower potable water from the network and reduce the associated energy consumption.

Energy-water intertwined effects

The results from the scenarios illustrate how water and energy system at local level are inter-related, through different examples. Under the net-zero target, the residential water heating (Fig. 13 in c.f. [supplementary information](#)) shows a complete transition from LPG and natural gas to thermal solar with electricity serving has backup, with an efficiency gain of 18% decrease in the energy consumption in 2050 comparing to 2015. Under the net-zero scenarios, water consumption in residential water heating reduces by 40% in the same period showing the benefits of energy-efficient appliances in lowering heated water use.

The adoption of water-energy highly efficient technologies, as cloth washing machines and dishwashers (Fig. 6) becomes cost-optimal to reduce both local water and energy consumption levels, even in the REF scenario. This supports the previous work on integrated water-energy strategies that induce resource sustainability [117,118]. Under the net-zero target scenarios, the energy consumption by these two appliances reduces 28% and 73% respectively in 2045 compared to 2015 because they are fully replaced with highly efficient equipment. Net-zero target also accelerate the adoption of highly efficient equipment as a strategy to reduce electricity consumption. This is particularly relevant to offset the increase electricity demand from other sectors, such as transport, as a solution to reduce GHG emissions.

Rainwater harvesting became a significant water source, accounting up to 8% of total water inflows, despite being limited to non-potable

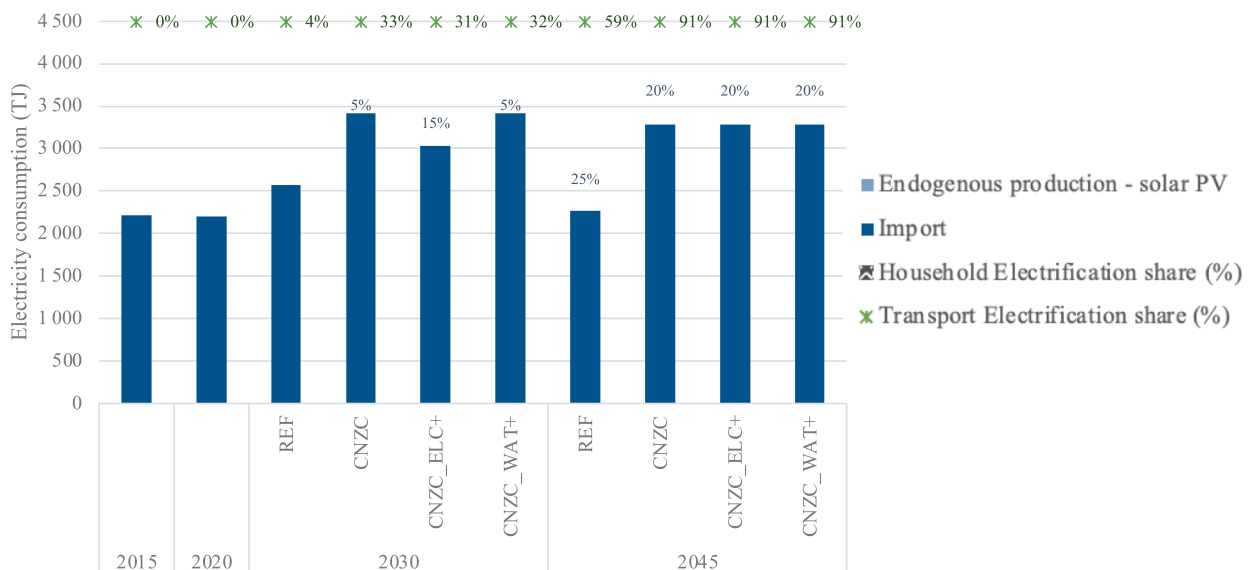


Fig. 5. Cascais municipality electricity sources in REF, CNZC, CNZC_ELC + and CNZC_WAT + scenarios.

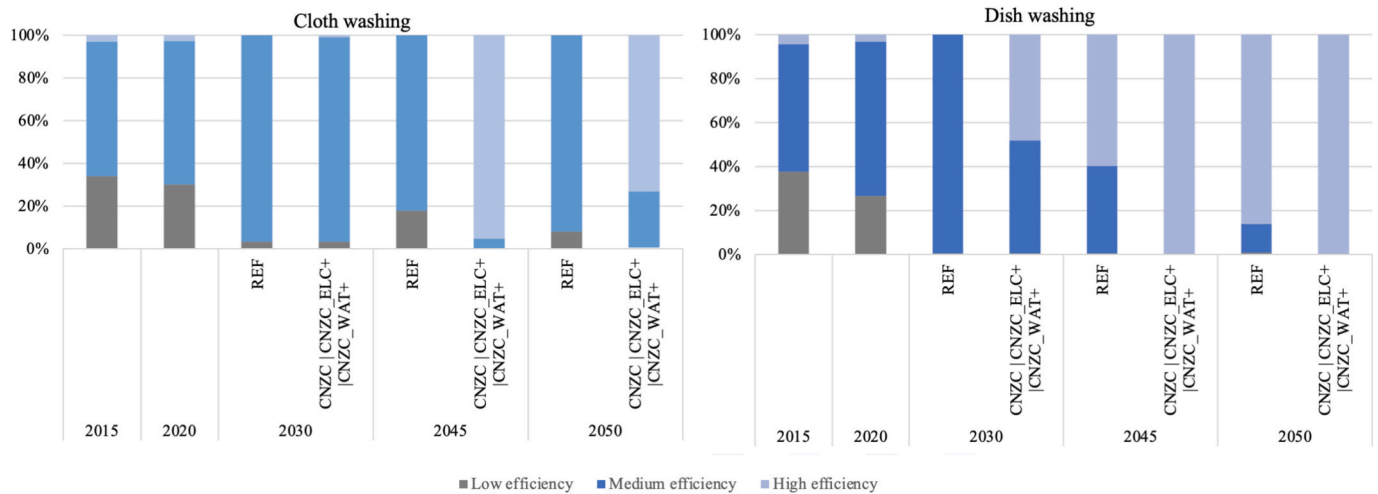


Fig. 6. Household clothes washing (left) and dish washing (right) machines stock share by energy label (Low efficiency: E – G energy efficiency labels; Medium efficiency: B energy efficiency label; High efficiency: A and A + G energy efficiency label).

uses in households, due to its ability to reduce energy consumption for water supply in comparison with other available options.

The analysis makes evident that GHG emission reduction target, usually analysed from an energy perspective alone, promotes significant beneficial spillover effects on water systems contributing to achieve higher levels of water self-sufficiency, as illustrated in Table 2. Lin et al. [119] study, using LEAP-WEAP model, highlighted that a scenario higher EV use in Xiamen would require energy-related water withdraw most of the energy transition technology deployment scenarios show co-benefits of potential savings in total energy consumption and total water withdrawal. The LEAP-WEAP coupling can provide useful insights [120], these approaches require external linkages between separate water and energy models, potentially missing optimization synergies that integrated approach captures endogenously. The availability of endogenous resources and decreasing costs of technologies determine the conditions to increase self-sufficiency. The net-zero goal promotes energy self-sufficiency from 6% up to almost 17% in 2030 and more than 32% in 2050, which increase to more than 22% and 34% respectively, when prices of electricity from the national grid double. Similarly for water system, solutions to collect endogenous water become cost-effective under a net-zero target, increasing self-sufficiency from 16% in 2015 to more than 24% in 2030 and almost 30% in 2050. Doubling water prices from outside the municipality has no impact in water self-sufficiency.

Conclusions

This paper explores the impacts of net-zero carbon emissions target in 2045 as well as energy and water resources pricing on the long-term water-energy interconnected systems configuration, to deliver the energy and water services demand up to 2050. We use an energy system optimization model at municipality/city scale, expanded to integrate the local water flows and technologies and its connections with the energy system, to generated four scenarios guided by mitigation targets and high resource prices.

The net-zero carbon emission target considering the integrated energy and water systems provides benefits in water consumption efficiency and decentralized solutions deployment (e.g. rainwater harvesting). Moreover, circular alternatives (e.g. household grey wastewater reuse) are also becoming cost-effective due to related energy efficiency.

Electrification from renewable sources is pivotal for climate change mitigation. However, due to imitated endogenous sources, an increase in electricity imported from outside the municipality boundaries may

happen, inducing external dependence of the municipality to comply with carbon neutrality goal. This may not be a problem if the national power system adopts deep decarbonization pathway, otherwise the municipality is trapped within its dependency.

Even in the absence of a net-zero goal, efficient transportation modes, like electric vehicles, and very efficient appliances are cost-effective and contribute to the decarbonization of the municipality's energy system by 73% till 2050, contingent upon the carbon content of the electricity, particularly if sourced from renewable energy. The net-zero carbon target promotes energy and water self-sufficiency, reaching levels up to 33% and 29%, respectively, in 2045. This progress is driven by the increasing cost-effectiveness of endogenous resources-based technologies, particularly solar thermal and PV system and rain-water harvesting solutions. These results prompt high ambition on local level policies and resources management, increasing the role of local governance structures and political responsibility and commitment, with sustainable future pathways of the municipality. Moreover, these findings align local strategies and the support of climate neutrality National and European Green Deal objectives and its core principle: energy efficiency first. The findings highlight the necessity of policy ambition and commitment for EU's Circular economy plan on resource efficiency promotion has also close relation with decentralized solutions, electrification in achieving sustainable energy and water management.

Also, the solution deployment can face additional challenges at multi-level structures such as higher national policy alignments and community and citizens financial and preferences of investment. Present study acknowledges important limitations such as it does not consider other relevant determinants socio-political factors on water-energy system technology deployment. Future work can focus on integrate societal factors alongside technical and economic optimization for successful implementation of sustainable solutions. Another limitation is model transferability. Although the developed model and approach could potentially be applied to other municipalities, the high data intensive requirements and access to detailed data on local energy and water systems may restrict the adaptation to various circumstances. Nevertheless, research can target the match between model requirements and local statistics systems development. Also, current study primarily focused on technical feasibility and general cost-effectiveness rather than specific financial instruments or incentive structures. Therefore, future research can explore the necessity to define robust financing mechanisms and economic incentives for large-scale deployment of all highlighted technologies as a complement to the findings of this study. Future research can also focus on the impact of seasonal endogenous water and energy resources variations associated with

climate change impacts and higher tourism rates.

CRedit authorship contribution statement

Luís P. Dias: Writing – original draft, Methodology, Investigation, Conceptualization. **Júlia Seixas:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Luis Dias reports financial support was provided by NOVA University of Lisbon Center for Environmental and Sustainability Research. Luis Dias reports a relationship with NOVA University Lisbon NOVA School of Science & Technology that includes: employment. 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seta.2026.104930>.

Data availability

Data will be made available on request.

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